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GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

PROJECT INITIATION

Date: March 31, 1975

Project Title: Define Conceptional Design of an On-Board Optical Processor with Components

Project No.: A-1719

Project Director: Mr. J. R. Walsh

Sponsor: NASA - Marshall Space Flight Center; MSFC, Ala. 35812

Agreement Period: From March 10, 1975 Until Aug. 9, 1975 (Contract Term)

Type Agreement: Contract No. NAS8-31344

Amount: $59,799 Title to GIT-

Reports Required: Monthly Progress, Final Report Requires NASA approval of item purch. over $1000

Sponsor Contact Person:

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George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Administrative Matters
Thru GTRI
Mr. R. J. Whitcomb (ACO)
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Defense Priority Rating: DO-A2 under DMS Reg. 1

Assigned to: COMMUNICATIONS

COPIES TO:

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Mr. R. G. Shackelford (A-1719-001)
Mr. J. W. Dees (A-1719-001)

RA-3 (3-75)

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: 4/21/77

Project Title: "Conceptual Design of an On-Board Optical Processor with Components."

Project No: A-1719

Project Director: Mr. J. R. Walsh

Sponsor: NASA - Marshall Space Flight Center

Effective Termination Date: 1/9/77

Clearance of Accounting Charges: 1/31/77

Grant/Contract Closeout Actions Remaining:

- x Final Invoice and Closing Documents
- _ Final Fiscal Report
- x Final Report of Inventions
- x Govt. Property Inventory & Related Certificate
- _ Classified Material Certificate
- _ Other ______

Assigned to: Electronics Technology (School/Laboratory)

COPIES TO:

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CA–4 (3/76)

A-1719

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Systems & Techniques Department
Communications Division

Define Conceptional Design of an On-Board Optical Processor with Components

Monthly Progress Report No. 1

10 March 1975 to 31 March 1975

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729 (IF)

11 April 1975

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

11 April 1975

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF 13

Subject: Monthly Status Project No. 1, Project A-1719, "Define Conceptional Design of an On-Board Optical Processor with Components" covering Period 10 March 1975 to 31 March 1975, Contract NAS8-31344, Control No. 1-5-56-50729 (IF).

Gentlemen:

During this period, work on the project has been directed to the review of possible optical processor configurations and to review of the literature relating to optical processors and related equipment. A strong candidate for the optical processor to be considered for conceptual design is the image change detector. Two basic configurations of this type processor are being considered. One configuration uses beam splitters to co-align the image and filter function; the other imposes the image and filter function on the transform plane from different directions.

The literature review has resulted in the collection of more than twenty papers in the field of optical processing and related techniques. A review of this literature is underway.

Early in the next period a trip is planned to MSFC to more clearly define the goals of the project. Participating in the review will be Georgia Tech personnel whose specialities are in the fields of electronics, optics, and mechanical design.

During the next period an optical processing system for which the conceptual design will be carried out will be selected. Once the specific system configuration is selected the size of the processor can be determined and the mechanical requirements of the optical portion of the processor clarified. The literature review will continue. Characteristics of the critical image forming device will be investigated and techniques for forming the images in these devices will be reviewed.

The following information is relative to the contract for the period 10 March 1975 through 31 March 1975:

Contract Value:	$59,799
Expenditures this period:	1,939
Expenditures to date:	1,939
Estimated funds to completion:	57,860

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully submitted,

J. R. Walsh, Jr.
Project Director

JRW:swg

Approved:

D. W. Robertson, Chief
Communications Division

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Systems & Techniques Department
Communications Division

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report No. 2

1 April 1975 to 30 April 1975

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF)

13 May 1975

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

13 May 1975

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF 13

Subject: Monthly Status Report No. 2, Project A-1719, "Define Conceptional Design of an On-Board Optical Processor with Components", covering period 1 April 1975 to 30 April 1975, Contract NAS8-31344, Control No. 1-5-56-50729(IF).

Gentlemen:

A visit was made to MSFC on 3 and 4 April 1975 during which the direction of the technical effort on the project was discussed. Included in the Georgia Tech personnel who made the trip were representatives of optical, mechanical, and electronic disciplines. The discussions concerned the requirements of an on-board optical processor to be placed aboard a manned spacecraft for the major purpose of data reduction of television formatted data. A prime candidate for such a system is an optical image change detector.

Since the visit to MSFC, several optical correlation configurations have been evaluated for application to image change detection. An analysis of the required mathematical operation has shown that cross correlation of two images with zero offset can be accomplished by simple image casting on one extreme or by variations of the more complicated spatial heterodyning system on the other extreme.

Image casting, by projecting one image through a transparency of another image located in the front focal plane of a lens, can be accomplished with two incoherent-to-coherent imaging devices and a simple optical system. The cross correlation of the two images appears at the back focal point of the lens along with the undiffracted light component. The undiffracted light can be removed by high pass spatial filtering of one of the two projected light images. Although this system is inherently simple, it is very susceptible to relative displacements of the two image planes in directions perpendicular to the optic axis. Thus, relative displacements of two identical images within their fields of view would reduce the correlation amplitude and result in transmission of redundant data in some applications.

The spatial heterodyne system requires three incoherent-to-coherent converters, but has the advantage of being tolerant to image plane displacements perpendicular to the optic axis. The result of a relative displacement of two identical images within their fields of view in this configuration is a corresponding shift of the correlation peak in the detector plane. Thus, by scanning the detector plane and performing appropriate electronic logic operations, a change in the image could be discriminated from a single displacement of two identical images.

The requirements on incoherent-to-coherent converter operating parameters and the dimensional stability required for each type of correlation system is being studied. The design philosophy is to minimize the number of optical components and mechanical complexity of the required geometry for performing the desired mathematical operation. Passive techniques for achieving dimensional stability will be considered as the primary means of maintaining optical system alignment; however, closed loop control will be exploited as required.

The image change detection concept requires temporary storage of a reference frame of data which is updated only when the succeeding frames of data undergo sufficient change. The electronic storage and scan conversion required to store and input the reference image onto the incoherent-to-coherent converter involves highly sophisticated and costly equipment. Conceptually, this operation could be carried out with an optical storage device with a significant reduction in equipment complexity. The type of device required is an incoherent-to-coherent converter with memory and write-erase capability. The requirements for such an optical storage device will be included in the study of materials and techniques relating to incoherent-to-coherent converters.

During the next period other selected optical processing techniques will be investigated and methods of implementation for spacecraft use will be studied. In particular, techniques which apply more to multispectral scanners than to television formats such as the image change detector will be investigated. Materials for possible use in construction of the optical process will continue to be studied. A visit to MSFC is planned early in the next period to review the project technical status with MSFC technical representatives.

The following information is relative to this contract for the period 1 April to 30 April 1975:

Contract Value	$59,799
Expended this period:	6,315
Expended to date:	8,254
Estimated funds to completion:	51,545

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully submitted,

J. R. Walsh
Project Director

JRW:gh

Approved:

D. W. Robertson, Chief
Communications Division

A-1719

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Systems & Techniques Department
Communications Division

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report No. 3

1 May 1975 to 31 May 1975

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF)

10 June 1975

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

10 June 1975

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF 13

Subject: Monthly Status Report No. 3, Project A-1719, "Define Conceptional Design of an On-Board Optical Processor with Components," covering period 1 May 1975 to 31 May 1975, Contract NAS8-31344, Control No. 1-5-56-50729(IF).

Gentlemen:

A visit was made to MSFC from 30 April to 2 May 1975 to discuss the possible configurations of the optical processor and to discuss some of the possible applications of such a device. At that time it was decided to investigate the application of an optical processor to data produced by multispectral scanners such as those used on the Earth Resources Satellite and those included on the proposed Earth Observatory Satellite.

During this period the characteristics of multispectral scanners have been reviewed. Discussions were held with Georgia Tech personnel who have been processing ERTS data to produce land use maps. The scanning methods used in the multispectral scanners and techniques for processing the data were reviewed. Digital processing techniques used to process the ERTS data generally make use of only the spectral outputs of the scanners in several bands to produce a vector in each band which is used to classify the data into appropriate categories. Some processing techniques make use of spatial frequency data to produce additional vectors for classification. Presently this spatial frequency data is produced digitally using the fast Fourier transform algorithm, and analysis of data using this technique requires a considerable expenditure of computer time. Optical techniques have been proposed for generating spatial frequency data for small surface areas around the ground point of interest and for producing additional vectors for classification purposes. The form of the on-board processor to accomplish this operation was investigated. Light emitting diode arrays (made up of individual diodes) were considered for input devices, and charge coupled devices for use in the spatial frequency plane were investigated. A small special purpose on-board processor for producing the spatial frequency data was envisioned which, when coupled with an on-board digital processor, might allow classification of land use at the space platform rather than on the ground. On-board processing would greatly reduce the data which would need to be transmitted.

Later in the period the use of an optical processor for cloud tracking purposes was briefly considered.

Since none of these special purpose uses of an on-board optical processor are well defined at this time, the decision was made jointly by Georgia Tech and MSFC personnel to pursue the conceptual design of an on-board general purpose processor capable of spatial filtering and correlation. Two configurations of such a processor are presently under investigation. One uses a straight through configuration of two tandem optical transforms with a dc block in the first transform plane to produce an on-axis correlation spot in the second transform plane. The other uses a single transform with two images in the input plane to produce an off-axis correlation spot in the output retransform plane.

Review of incoherent-to-coherent light valves has continued during this period. Since these devices are critical to the operation of the processor, the collection of data on these devices is receiving a major portion of the project effort at this time.

During the next period collection of information on light valves will continue. Visits are planned during the next period to manufacturers of the most promising devices to collect detailed information on performance characteristics. Devices such as liquid crystals and PROM's are relatively new, and developments are changing rapidly; therefore, direct contact with selected manufacturers is essential. Oil film devices have been used for many years for projection of television pictures, and these devices are presently being adapted to operate with coherent light.

Research on materials to be used in an optical processor will continue during the next period. A review of the status to date is being prepared.

The following information is relative to this contract for the period 1 May to 31 May 1975:

Contract Value:	$59,799
Expended this period:	5,742
Expended to date:	13,996
Estimated funds to completion:	45,803

National Aeronautics and Space Administration
10 June 1975
Page Three

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully submitted,

Joseph R. Walsh, Jr.
Project Director

JRWjr/gh

Approved:

FOR D. W. Robertson, Chief
Communications Division

A-1719

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Systems & Techniques Department
Communications Division

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report No. 4

1 June 1975 to 30 June 1975

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF).

14 July 1975

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

14 July 1975

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF 13

Subject: Monthly Status Report No. 4, Project A-1719, "Define Conceptional Design of An On-Board Optical Processor with Components", covering period 1 June 1975 to 30 June 1975, Contract NAS8-31344, Control No. 1-5-56-50729(IF)

Gentlemen:

During this period visits have been made to several manufacturers of coherent light valves, a manufacturer of optical processing equipment, and two NASA centers to obtain information relevant to the contract.

The coherent light valve manufacturers visited were General Electric in Syracuse, New York, the ITEK Corporation in Lexington, Massachusetts, and the Hughes Research Laboratories in Malibu, California. General Electric and ITEK were visited on the 12th and 13th of June. At General Electric their coherent light valve (CLV) was discussed. This device uses a thin film of "oil" on an optical substrate which is written on by an electron beam. This causes the oil to deform which phase modulates a light beam that is projected with a Schlieren optical system. The device was originally developed as a television projection device and modified for coherent operation. It involves the complexity of an electron beam system and the considerations of controlling the oil in a space environment. At ITEK the pockels readout optical modulator (PROM) was discussed. This device utilizes a bismuth silicon oxide crystal which is written on with blue light and read with red light. Operation of the device requires that several kilovolts be switched across the crystal. The visit to Hughes was made on 25 June, and their photoactivated liquid crystal light valve was discussed. It utilizes a liquid crystal which is a-c operated with approximately 6V RMS at 10 kHz. It is constructed utilizing thin film technology and has the potential for low cost in production.

A compilation of the characteristics of these devices is underway so that their suitability for image plane and transform plane input devices for a real time optical processor may be evaluated.

Visits were also made to NASA Ames Research Center, to the Jet Propulsion Laboratory, and to Goodyear Aerospace Corporation, during the trip to the west coast, where various aspects of optical processing were discussed.

During the next period the various input devices will continue to be evaluated. A configuration of a general purpose real time optical processor will be selected and the mechanical design of such a processor will be considered. A visit to MSFC to review the project with the technical monitor will be made early in the next period.

The following information is relevant to the contract for the period 1 June to 30 June 1975:

Contract Value	$59,799
Expended this Period	6,712
Expended to Date	20,709
Estimated Funds to Completion	39,090

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully submitted,

Joseph R. Walsh, Jr.
Project Director

JRW:gh

Approved:

D. W. Robertson, Chief
Communications Division

A1719

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Systems & Techniques Department
Communications Division

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report No. 5

1 July 1975 to 31 July 1975

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF).

13 August 1975

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

13 August 1975

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF 13

Subject: Monthly Status Report No. 5, Project A-1719, "Define Conceptional Design of An On-Board Optical Processor with Components", covering period 1 July 1975 to 31 July 1975, Contract NAS8-31344, Control No. 1-5-56-50729(IF)

Gentlemen:

A visit was made to MSFC on 9 and 10 July to discuss the results of the visits to manufacturers of incoherent-to-coherent image input and Fourier plane devices for optical processors. The devices reviewed were the coherent light valve (CLV) manufactured by General Electric, the pockels readout otpical modulator (PROM) manufactured by the ITEK Corporation, and the photoactivated liquid crystal light valve manufactured by Hughes. Also reviewed in the area of optical processors was the information obtained during visits to the NASA Ames Research Center, the Jet Propulsion Laboratory, and the Goodyear Aerospace Corporation.

During the past reporting period a study of operating characteristics relating to optical performance of incoherent-to-coherent imaging devices has been performed. The input-output characteristics of the major devices have been analyzed, and a common set of descriptive parameters has been identified. For coherent imaging applications, four parameters assume primary importance: (1) for a device which is illuminated with incoherent radiation, and read out with coherent radiation, the dynamic range is defined as the range of incoherent input exposure over which the coherent output intensity is smoothly changing, (2) the contrast ratio is defined as the ratio of coherent light intensity output with no exposure to the output with an input intensity which results in saturation, (3) the signal-to-noise ratio is defined as the output signal-to-background ratio measured in the Fourier transform plane and is a function of spatial frequency, and (4) the resolution is given in terms of the number of lines per millimeter for 50 percent degradation of the modulation transfer function. While these parameters are not always given for a particular device, they can usually be calculated from other published data. In addition to providing a means for direct comparison between this class of imaging devices, these parameters also provide the basis for comparison with photographic film, which has been the standard media for coherent optical input data.

Other characteristics of imaging devices relating to lifetime, sensitivity, drive requirements, and cost have also been investigated and will be discussed in detail in the final report. The principal concern of this evaluation is to determine the suitability of this class of devices to on-board spacecraft optical processing systems. To this end, the elements of lifetime, reliability, and environmental constraints will have equal importance with optical performance.

During the next period the preparation of the draft copy of the final report will be completed. This report will review the project activity and place a major emphasis on the input devices to an optical processor. These devices are considered to be the devices critical to a real time processor at the present time. A general configuration of an optical processor will be described which will allow spatial filtering and correlation to be performed. Mechanical considerations concerning the design of an optical processor will also be discussed.

The following information is relevant to the contract for the period 1 July to 31 July 1975:

Contract Value	$59,799
Expended this Period	9,500*
Expenditures to Date	30,209
Estimated Funds to Completion	29,590

*Fringe benefits for month of July not included.

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully submitted,

Joseph R. Walsh, Jr.
Project Director

JRW:gh

Approved:

D. W. Robertson, Chief
Communications Division

A- 1719

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Electromagnetics Laboratory

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Reports - Nos. 6, 7, 8

1 August to 31 August 1975
1 September to 30 September 1975
1 October to 31 October 1975

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF).

13 November 1975

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

November 13, 1975

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF 13

Subject: Monthly Status Reports Nos. 6, 7, and 8, Project A-1719, "Define Conceptional Design of An On-Board Optical Processor With Components," Covering periods 1 August to 31 August 1975, 1 September to 30 September 1975, and 1 October to 31 October 1975, Contract NAS8-31344, Contract No. 1-5-56-50729 (IF).

Gentlemen:

A ninety day extension in the period of performance has recently been received on the contract. The monthly reports and financial statements required due to the extension are combined in this document to bring the reporting requirements up to date.

During the periods covered by these reports, the primary objective was the reduction of the information collected on the components of an optical processor to a form suitable for inclusion in the final report. The item receiving the major portion of the project effort continues to be incoherent-to-coherent real time input devices for the optical processor. Devices which are prime candidates for the input device are the Hughes optical-to-optical interface device (OTTO) and the ITEK pockels read out optical modulator (PROM). Techniques for interfacing these devices with electronic signals generated by television cameras or multispectral scanners have been investigated. A survey of optical detectors required for the output plane of the optical processor has also been completed. The section on digital simulation for the final report has been completed and the preparation of the figures for that section is in progress.

During the next period the draft copy of the final report should be completed. This report will contain a detailed evaluation of input devices for an optical processor, a section on mechanical considerations, a section on electronic considerations, and the results of a digital simulation of certain aspects of optical processors. Conclusions and recommendations will conclude the report.

The following information is relevant to the contract for the period of 1 August to 31 August 1975:

Contract Value	$59,799.
Expended 1 August to 31 August	9,814.
Expenditures through 31 August	40,023.
Estimated Funds to Completion	19,776.

For the period of 1 September to 30 September 1975, the following additional information is relevant:

Expended 1 September to 30 September	$11,222.
Expenditures through 30 September	51,245.
Estimated Funds to Completion	8,554.

And for the period of 1 October to 31 October 1975 the following additional information is relevant:

Expenditures 1 October to 31 October	$ 3,214.
Expenditures through 31 October	54,459.
Estimate funds to completion	5,340.

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully submitted,

Joseph R. Walsh, Jr.

Approved:

R. G. Shackelford, Head
Electro-Optics Group

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Electromagnetics Laboratory

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report - No. 9

1 January to 31 January 1976

by

Josheph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF).

23 February 1976

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

February 23, 1976

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF 13

Subject: Monthly Status Report No. 9
Project A-1719, "Define Conceptual Design of An On-Board Optical Processor With Components," Covering Period 1 January to 31 January 1976, Contract NAS8-31344, Control No. 1-5-56-50729(IF).

Gentlemen:

Modification No. 3 to the contract has been received. This modification adds to the scope of work to be performed on the contract, extends the period of performance by nine months, and adds $39,909 to the funding of the contract.

The draft copies of the interim report were delivered during the period covered by this report and approval of the interim report was received. This report covered the work performed during the first ten months of the contract and was primarily concerned with the collection and evaluation of information relating to optical input devices for a real time optical processor. Optical input devices evaluated were the General Electric Coherent Light Valve, the ITEK Pockel's Readout Optical Modulator, the Hughes Liquid Crystal Modulator, and the Image Forming Light Modulator. Also investigated were the electrical-to-optical and optical-to-electrical interface requirements, optical processor mechanical considerations, and the digital simulation of certain aspects of optical correlation and liquid crystal decay characteristics.

The continuing effort on the contract is concerned with optical systems configured to perform optical correlation at television rates. Also of major interest in the continuing effort is the definition of specific applications which are uniquely suited to optical or hybrid optical-digital processing.

A visit was made to MSFC on 22 and 23 January 1976 to review the project objectives with the MSFC technical representatives and to begin the investigation of potential applications of an optical processing system.

A-1719

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Electromagnetics Laboratory

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report - No. 10

1 February to 29 February 1976

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF).

12 March 1976

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

March 12, 1976

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF13

Subject: Monthly Status Report No. 10, Project A-1719, "Define Conceptual Design of an On Board Optical Processor With Components," Covering Period 1 February to 29 February 1976, Contract NAS8-31344, Control No. 1-5-56-50729(1F).

Gentlemen:

During the period covered by this report the interim report describing the first ten months of effort on the contract was distributed. The interim report discussed several aspects of a real-time optical processor, among which were, (1) optical input devices, (2) mechanical considerations, (3) electrical-optical and optical-electrical interfaces, and (4) digital simulation of certain aspects of optical correlation processing and optical input device characteristics.

The major project effort during this period has been the investigation of potential applications of optical data processing. A review of future space shuttle sortie missions and automated payloads has continued. Among the items of iterest in this review are transmission data rates, volumes of both real time and stored data, television requirements and processing operations to be performed both on board the spacecraft and on the ground. From this review it is hoped that experiments which could profit from optical or hybrid optical-digital processing can be identified and that the processing requirements defined so that hardware configurations and processing techniques may be specified.

The information gathered and reviewed thus far has only indicated where possible applications of optical data processing may be. Because of the large number of experiments being reviewed, a selection is being made of only those which appear to be the most likely to benefit from optical data processing for detailed investigation on the first evaluation. The next step in identifying possible uses of optical data processing will be the more detailed evaluation of the data processing requirements of these selected experiments.

March 12, 1976
Page Two

During the next period the detailed evaluation of the selected experiments data processing requirements will begin. An attempt will be made to contact cognizant government personnel or principal investigators familiar with the details of the selected experiments. From this investigation of the actual data processing requirements it is hoped that specific uses of optical data processing may be identified.

The following information is relevant to the contract for the period of 1 February to 29 February 1976:

Contract Value	$99,708
Expended 1 February to 29 February	5,692*
Expenditures through 29 February	72,341
Estimated Funds to Completions	27,367

*Includes expenditures for retroactive salary increase to 9-1-75.

The total unexpended funds are considered adequate for satisfactory completion of the projected requirements.

Respectfully Submitted,

Joseph R. Walsh, Jr.
Project Director

Approved:

Robert G. Shackelford
Head, Electro-Optics Group

M-1719

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Electromagnetics Laboratory

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report - No. 11

1 March to 31 March 1976

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF)

15 April 1976

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

April 15, 1976

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF13

Subject: Monthly Status Report No. 11, Project A-1719, "Define Conceptional Design of an On-Board Optical Processor With Components," Covering Period 1 March to 31 March 1976, Contract NAS8-31344, Control No. 1-5-56-50729(IF).

Gentlemen:

During the period covered by this report the investigation of uses of optical or hybrid optical-digital processors has continued. The review of the space shuttle automated and sortie missions has revealed several experiments which will produce high real time data rates or which will produce large quantities of stored data to be transmitted to earth within the time of an orbit or in a day, or which will be physically returned. Several experiments have also been identified which will require some amount of on-board digital computer processing. Further investigation of these on-board processing requirements may identify specific processing needs which may be cost effectively met by optical or hybrid optical-digital processors.

Several contacts have been made with NASA centers in regard to data processing requirements in general and the possible applications of optical data processing. To date these contacts have revealed several non-space oriented applications for optical processing. These applications will be further investigated because of the possible related space applications which may emerge. An attempt will be made to meet with technical personnel involved with applications such as these for detailed discussions during several trips planned for the near future.

During the next period contacts with individuals familiar with data processing needs of future space missions will continue. An effort will be made to obtain enough of the contacts so that several trips may be made to obtain detailed information on data processing requirements and to identify those experiments which may use optical or hybrid optical-digital processing in a cost effective manner.

The following information is relevant to the contract for the period of 1 March to 31 March 1976:

Contract Value	$99,708
Expended 1 March to 31 March	2,689
Expenditures through 31 March	75,030
Estimated Funds to Completion	24,678

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully Submitted,

Joseph R. Walsh, Jr.
Project Director

Approved:

Robert G. Shackelford
Head, Electro-Optics Group

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Electromagnetics Laboratory

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report - No. 12

1 April to 30 April 1976

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF)

18 May 1976

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

May 18, 1976

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF13

Subject: Monthly Status Report No. 12, Project A-1719, "Define Conceptual Design of an On-Board Optical Processor With Components," Covering Period 1 April to 30 April 1976, Contract NAS8-31344, Control No. 1-5-56-50729(IF).

Gentlemen:

During the period covered by this report the investigation of uses of optical or hybrid optical-digital processors has continued. Based on a review of the space shuttle automated and sortie missions several earth observation experiments were selected having high data transmission rates or possible on-board digital image processing requirements. Contacts were made at NASA Headquarters and at Goddard Space Flight Center with personnel having knowledge of the requirements of these experiments as well as any other possible applications of optical processing. Based on these contacts a visit was made to the Washington D. C. area on 22 and 23 April, 1976 to discuss data processing requirements.

Discussions at GSFC involved individuals associated with mission utilization, missions and operations, and data analysis. The conclusion reached as a result of these discussions was that optical processing in general was undesirable. This conslusion was based largely on the views that (1) an optical processor is a special purpose processor possessing limited flexibility, (2) it is an analog processor with limited accuracy and (3) the rapid advances in digital processing are making possible digital processing of operations which are presently or have in the past been performed by optical processing.

It should be pointed out, however, that the present LANDSAT data system has 6 bit accuracy, and the proposed follow-on system based on the THEMATIC MAPPER is only an 8 bit system. It is not conclusive at this point, in view of the state-of-the-art, that competitive ODP systems could not be developed. It should also be noted that the special purpose digital computers which are capable of performing millisecond processing operations such as Fourier transforms cost several hundred thousand dollars. In view of the potential low cost of an ODP system, a hybrid optical-digital system concept might be appropriate for low cost real time processing applications. The possibility of any type of on-board processing for earth resources observations in the next five or ten years was considered remote because of the hesitancy to "throw away" any of the data generated by the spacecraft sensors.

Discussions at NASA headquarters involving microwave sensors were not as discouraging. Because of the extremely high data rates involved (to 300 Mbps) on-board processing has not been completely ruled out. The high data rate would be produced by an orbital synthetic aperture radar. The lack of flexibility of an optical processor was, however, again considered a drawback.

During the next period this investigation of uses of optical processors will continue. The major area where an application may exist appears at this time to involve the orbital microwave systems. Personnel knowledgable in this area will be contacted and appropriate visits will be made.

The following information is relevant to the contract for the period of 1 April to 30 April 1976:

Contract Value	$99,708
Expended 1 April to 30 April	2,716
Expended Through 30 April	77,746
Estimated Funds to Completion	21,962

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully Submitted,

Joseph R. Walsh, Jr.
Project Director

Approved:

Robert G. Shackelford
Head, Electro-Optics Group

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Electromagnetics Laboratory

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report - No. 13

1 May to 31 May 1976

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF)

17 June 1976

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

June 17, 1976

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF13

Subject: Monthly Status Report No. 13, Project A-1719, "Define Conceptual design of an On-Board Optical Processor With Components," Covering Period 1 May to 31 May 1976, Contract NAS8-31344, Control No. DCN 1-5-56-50729(IF).

Gentlemen:

During the period covered by this report the major project effort has been directed toward contacting personnel knowledgeable with possible applications of space oriented optical or hybrid optical-digital processing. Orbital microwave systems are being investigated as candidate systems which may effectively use such processing techniques primarily because of the possible reduction in the high data rates associated with some of these systems. Such a system is the future orbital synthetic aperature radar. Preliminary discussions with technical personnel associated with this system indicate that since the early systems will be experimental in nature, there is a hesitancy to process the data on-board to reduce the communication channel data rate, since the detailed characteristics of the data which will be received will not be known until the system is operating in orbit. These discussions also revealed that if on-board processing were to be used the present inclinations would be to use digital rather than optical techniques. The reasons for the present preference for digital techniques are future development prospects for digital systems and the flexibility offered by digital processors. This hesitancy to "throw-away" any of the data produced by an orbital sensor and the preference for digital techniques corresponds to that found earlier in the program for earth observation sensors.

As a result of the contacts which have been made preliminary information has been obtained on a couple of other processing applications to which optical data processing may apply. One of these is understood to involve the use of transform techniques to increase the resolution of orbital sensors, and the other is understood to involve the use of the level slicing capabilities of devices like the ITEK PROM to classify remotely sensed data using the cluster mapping techniques previously employed in digital systems. The details of these possible applications still need to be investigated and will be pursued further during the next period.

During the next period the investigation of applications of optical or hybrid optical-digital processing will continue. If warranted, visits will be made to appropriate centers to discuss in detail possible applications of optical data processing. A review of the current literature which is presently in progress will continue.

The following information is revelant to the contract for the period of 1 May to 31 May 1976:

Contract Value	$99,708
Expended 1 May to 31 May	$3,116
Expended Through 31 May	$80,861
Estimated Funds to Completion	$18,847

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully Submitted,

Joseph R. Walsh, Jr.
Project Director

Approved:

Robert G. Shackelford
Head, Electro-Optics Group

JRW/lcr

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Electromagnetics Laboratory

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report - No. 14

1 June to 30 June 1976

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF)

15 July 1976

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

July 15, 1976

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF13

Subject: Monthly Status Report No. 14, Project A-1719, "Define Conceptual Design of an On-Board Optical Processor With Components," Covering Period 1 June to 30 June 1976, Contract NAS8-31344, Control No. DCN 1-5-56-50729(IF).

Gentlemen:

During this period the effort to contact personnel knowledgeable in the space oriented applications of optical data processing or hybrid optical-digital data processing has continued. As a result of various telephone contacts, a visit was made on 23 June to the Jet Propulsion Laboratory and on 24 June to the Johnson Space Center. At JPL optical processing of air-borne synthetic aperture radar (SAR) data and the future SEASAT processing approaches were discussed. The ground-based optical system processes film recorded on-board an aircraft during operation of the SAR. Due to the large data format required for SAR it is doubtful that present state-of-the art real-time optical input devices could replace the film as the input medium to the optical processor. The current input format for the optical processor also requires a moving input medium, and this requirement would present a formidable problem in the implementation of a replacement real time input medium. The SEASAT (SAR) processor is intended to be digital, however an optical system will be developed as a back-up due to uncertainties in development of the digital processing system. Digital processing seems to be preferred because of the present state-of-the art in digital techniques, the limited accuracy of analog systems, the flexibility afforded by digital systems, and the potential advancement in the digital state-of-the art. Optical techniques may find application where speed is a critical factor, for applications where specific data processing techniques which may be performed by optical processing can be defined, and for applications where minimizing costs is a controlling factor.

A potential use of optical data processing is that of providing a real time monitor for a quick-look application or screening of the data to select desirable data for full transmission. Deep space SAR's also present a possible use of on-board optical processing because of the limited communication channel capacity available. The addition of a data channel on future multispectral scanners to transmit texture information obtained from a sensor with higher resolution than those which will normally be transmitted presents another possible application, although at this time it appears that Fourier techniques are only one of several possible methods of obtaining the measure of texture.

Because of the high data rate requirements of the SAR and the limited power which will be available from the shuttle, on-board processing has not been ruled out. These power limitations are a factor controlling the amount of on-board processing which may be performed. Optical data processing may be useful for on-board processing if it can be shown to reduce the power requirements while maintaining the accuracy and dynamic range requirements of the radar system.

During the next period the investigation of space oriented applications of optical data processing will continue. Contact with individuals in the optical processing community will continue as will that with individuals knowledgeable with future space applications of processing techniques.

The following information is relevant to the contract for the period of 1 June to 30 June 1976:

Contract Value	$99,708
Expended 1 June to 30 June	3,374
Expended through 30 June	84,236
Estimated Funds to Completion	15,472

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully Submitted,

Joseph R. Walsh, Jr.
Project Director

Approved:

Robert G. Shackelford
Head, Electro-Optics Group

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Electromagnetics Laboratory

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report - No. 15

1 July to 31 July 1976

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF)

1 September 1976

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

September 1, 1976

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF13

Subject: Monthly Status Report No. 15, Project A-1719, "Define Conceptual Design of an On-Board Optical Processor With Components," Covering Period 1 July to 31 July 1976, Contract NAS8-31344, Control No. DCN 1-5-56-50729(IF).

Gentlemen:

During the period covered by this report, the investigation of applications of optical or hybrid optical-digital data processors has continued. The investigation has revealed numerous industrial applications of optical techniques in the areas of quality control and precision measurement. Several possible space oriented applications have been mentioned in technical discussions with personnel knowledgable with future space missions. Among these applications are a quick-look ability for high information content imagery data, and deep space data reduction desirable because of the limited communication channel capacity. Although digital techniques are presently being considered, their inherently high power comsumption is causing concern, and a competitive low power drain optical data processing system would present an attractive alternative for on-board processing. In this application, the higher accuracy and flexibility of a digital processor would be traded off for low power consumption and reduced system complexity inherent with an optical processor.

Methods of using the presently available real time optical incoherent-to-coherent input devices in an optical correlator are being considered. The input devices being considered are the General Electric coherent light valve, the ITEK Pockel's effect optical modulator, and the Hughes liquid crystal input device. Unfortunately, none of these devices combine all the properties required of the object plane and spatial frequency plane devices for real time optical data processing. A combination of two of these devices may prove to be reasonable for a general system configuration.

Work will continue in the areas of investigation of space oriented application of optical data processing and methods of using presently available optical input devices in an optical correlation during the next period. The draft copy of the final report will be prepared.

The following information is relevent to the contract for the period of 1 July to 31 July 1976:

Contract Value	$99,708
Expended 1 July to 31 July	3,138
Expended through 31 July	87,374
Estimated Funds to Completion	12,334

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully Submitted,

Joseph R. Walsh, Jr.
Project Director

JRW/lcs

Approved:

Robert G. Shackelford
Chief, Electro-Optics Division

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Electromagnetics Laboratory

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report - No. 16

1 August - 31 August 1976

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF)

27 September 1976

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

September 27, 1976

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF13

Subject: Monthly Status Report No. 15, Project A-1719, "Define Conceptual Design of an On-Board Optical Processor With Components," Covering Period 1 August to 31 August 1976, Contract NAS8-31344, Control No. DCN 1-5-56-50729(IF).

Gentlemen:

During the period covered by this report the study of optical correlators and the investigation of applications of optical or hybrid optical-digital processors has continued. During the period investigators associated with the project attended the Society of Photo-Optical Instrumentation Engineers Symposium held 23 to 27 August, 1976 in San Diego, California. The siminars making up the symposium provided a means of obtaining up-to-date information revelent to optical correlators and optical data processors.

Several recent developments relating to optical correlators have come to the attention of the investigators on the project. Preliminary consideration of these developments indicates that the contract will benefit from further consideration of these developments and their possible inclusion in the specification of the optical correlator under study on the contract. These developments include the use of Millin transforms to reduce the dependence of correlation on size and rotation of the two images to be correlated, the use of Electro-Optic image intensifiers to increase the radiometric sensitivity of real time input devices, and the use of complex exponention of input images to enhance the amplitude of the correlation peaks in relation to the background amplitude in the correlation plane. A ninety day time extension of the contract has been requested so that these technical areas may be evaluated in relation to the optical correlator being considered.

Work will continue in these areas of investigation during the next period. Preparation of the draft copy of the final report will also continue.

The following information is revelent to the contract for the period 1 August to 31 August 1976:

Contract Value	$99,708
Expended 1 August to 31 August	4,641
Expended through 31 August	92,015
Estimated Funds to Completion	7,693

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully Submitted,

Joseph R. Walsh, Jr.
Project Director

JRW/lcs

Approved:

Robert G. Shackelford
Chief, Electro-Optics Division

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Electromagnetics Laboratory

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report - No. 17

1 September - 30 September 1976

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF)

27 October 1976

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

October 27, 1976

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF13

Subject: Monthly Status Report No. 17, Project A-1719, "Define Conceptual Design of an On-Board Optical Processor with Components," Covering Period 1 September to 30 September 1976, Contract NAS8-31344, Control No. DCN 1-5-56-50729(IF).

Gentlemen:

During the period covered by this report the investigation of optical correlators and the applications of optical and optical-digital data processors has continued. The major portion of the work during this period has been in the area of digital simulation of optical data processors. Earlier in the project a digital simulation program was generated which provided a means for simulation of a joint transform correlation processor. This simulation program was used to study optical correlators and the results were published in the interim report.

The digital simulation program is now being used to study two other aspects of optical correlators. The first of these is to determine the effect of phase instead of amplitude encoding of the input images on the correlation peaks in the output plane. Other investigators have reported a marked increase in the amplitude and sharpness of the correlation peaks when using this approach to encoding. This technique appears to be most useful when correlating dense images.

The second technique under investigation by digital simulation is that of the use of the Mellin transform to reduce the sensitivity of the transform components to the size and angular orientation of the input images. An approach under investigation makes use of a rectangular to polar conversion to separate the size and rotational variations, application of the Mellin transform to the radial components of the data, and application of the Fourier transform to the angular components of the data to reduce the sensitivity of the transform component to both size variations and rotation of the input images.

Work will continue on the digital simulation during the next period. The digital simulation presently being used makes use of single dimension transforms which allows the sensitivity of transform components to input object scale variation to be studied. Study of both the size and rotational effects will require the implementation of the two dimensional simulation program. If the single dimensional investigations warrent, this will be done during the next period.

The following information is revelent to the contract for the period 1 September to 30 September 1976:

Contract Value	$99,708
Expended 1 September to 30 September	3,251
Expended through 30 September	95,265
Estimated Funds to Completion	4,443

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully Submitted,

Joseph R. Walsh, Jr.
Project Director

JRW/dgk

Approved:

Robert G. Shackelford
Chief, Electro-Optics Division

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Electromagnetics Laboratory

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report - No. 18

1 October - 31 October 1976

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344

Control No. DCN 1-5-56-50729(IF)

22 November 1976

(Ga. Tech. Project No. A-1719)

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

November 22, 1976

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF13

Subject: Monthly Status Report No. 18, Project A-1719 "Define Conceptual Design of an On-Board Optical Processor with Components," Covering Period 1 October to 31 October 1976, Contract NAS8-31344, Control No. DCN 1-5-56-50729(IF).

Gentlemen:

During the period covered by this report various aspects of optical correlators and the various applications of optical and optical-digital optical processors has continued. The major portion of the project effort has been directed toward the study of the Mellin transform as it is related to optical processors. Image translational independence in a joint transform optical processor, in which the two input images are coplanar in the input plane, is provided by the spatial invariance property of the Fourier transform. Application of a polar to rectangular coordinate conversion in the transform plane of an optical processor seperates the size and rotational transform components of the input image. Retransforming with the Mellin transform for the radial component and the Fourier transform for the angular component should yield a transform with components independent of input image size and rotational variations.

Studies of the Mellin transform have been carried out during this period, both from a mathematical viewpoint and by digital simulation. The mathematics of the transform appear to be in order while the simulation has not as yet produced the expected results.

These investigations will continue during the next period. The draft copy of the final report will continue to be prepared.

The following information is relevant to the contract for the period 1 October to 31 October 1976:

Contract Value	$99,708
Expended 1 October to 31 October	1,746
Expended through 31 October	97,012
Estimated Funds to Completion	2,696

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully Submitted,

Joseph R. Walsh, Jr.
Project Director

JRW/dgk

Approved:

Robert G. Shackelford
Chief, Electro-Optics Division

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Electromagnetics Laboratory

DEFINE CONCEPTIONAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

Monthly Progress Report - No. 19

1 November - 30 November 1976

by

Joseph R. Walsh, Jr.

Contract No. NAS8-31344
Control No. DCN 1-5-56-50729(IF)

28 December 1976

(Ga. Tech. Project No. A-1719)

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

December 28, 1976

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

Attention: EF13

Subject: Monthly Status Report No. 19, Project A-1719 "Define Conceptual Design of an On-Board Optical Processor with Components," Covering Period 1 November to 30 November 1976, Contract NAS8-31344, Control No. DCN 1-5-56-50729(IF).

Gentlemen:

During the period covered by this report the application of optical and optical-digital data processors has continued to be investigated. Various aspects of optical correlators have also been studied. In particular the size and rotational invariance properties of the Mellin transform were considered. A digital simulation of a technique that is said to make the transform of the input data size and rotationally invariant has been attempted. This technique performs a rectangular to polar conversion of the transformed input data to seperate the size and rotational transform products of the input images. The transformed data after the polar transformation has a log scale applied to the radial component of the data while the angular information is unchanged. Applying the two dimensional Fourier transform should then yield an invariant output transform. The simulation has been generated but size invariance in the output data has not as yet been demonstrated.

During the next period the Mellin transform techniques will be persued further as time permits. The draft copy of the final report will be prepared.

The following information is revelent to the contract for the period 1 November to 30 November 1976:

Contract Value	$99,708
Expended 1 November to 30 November	2,000
Expended through 30 November	99,012
Estimated Funds to Completion	696

The total unexpended funds are considered adequate for satisfactory completion of the project requirements.

Respectfully Submitted

Joseph R. Walsh, Jr.
Project Director

JRW/dgk

Approved:

Robert G. Shackelford
Chief, Electro-Optics Division

A-1719

INTERIM REPORT

Project A-1719

CONCEPTUAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

J. R. WALSH, R. G. SHACKELFORD, R. D. WETHERINGTON, R. SHEPPARD

CONTRACT NAS8-31344

9 January 1976

Prepared for
NATIONAL AERONAUTICS & SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA

1976

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Atlanta, Georgia

INTERIM REPORT

Project A-1719

CONCEPTUAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

By

J. R. WALSH
R. G. SHACKELFORD
R. D. WETHERINGTON
R. SHEPPARD

CONTRACT NAS8-31344

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA

ABSTRACT

This report summarizes the investigations performed on Contract NAS8-31344 to date. The objective of this investigation was the specification of components for a spacecraft on-board optical processor. The investigation confirmed that real-time optical processing has made significant advances over the past few years, but that there are still critical components which will require further development for use in an on-board optical processor. The most critical component for a real-time optical processor is the real-time optical input device. A major part of this program was the collection and evaluation of information on these devices. The devices evaluated were the General Electric Coherent Light Valve, the ITEK Pockels Readout and Optical Modulator, the Hughes Liquid Crystal Modulator, and the Image Forming Light Modulator. The ITEK PROM and Hughes Liquid Crystal devices were identified as the primary candidates for the real-time input device of an optical processor although neither device could be judged at this time as completely satisfactory for the subject application.

Also investigated were the electrical-to-optical and optical-to-electrical interface requirements. Since a spacecraft mission has not been selected at this time, the investigation of interface requirements was approached from a basis which would apply to a wide spectrum of image sensors and data processing electronics. Mechanical considerations of a spacecraft processor were also considered on a general basis.

A digital computer simulation of optical correlation processing and the effect of optical input device decay time constants is also presented.

PREFACE

This report covers work performed under Contract NAS8-31344 for the period 10 March 1975 through 9 January 1976. It is the culmination of a preliminary study of the application of coherent optical processing to on-board satellite data management systems, and represents the final report on that phase of the continuing program under Contract NAS8-31344. This program was performed under the technical cognizance of Messrs. J. H. Kerr and H. F. Smith, Code EF13, NASA-Marshall Space Flight Center, and their interest throughout this study is gratefully acknowledged. In addition to the listed authors, Mr. A. McSweeney and other members of staff of the Engineering Experiment Station also contributed to this program.

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I. INTRODUCTION

Image processing techniques involve data with two dimensions of spatial extent having an intensity variation which provides the image gray scale information. Processing operations include correlation, spatial filtering, edge enhancement, pattern recognition and many others. The Fourier transform is a powerful linear operation on image data which provides the spatial frequency representation of the two dimensional image data. There are two basic methods by which the spatial frequency representation of image data may be obtained. One of these makes use of the serial representation of the image data, and by means of a digital computer applies the desired mathematical operation to the data so represented. The second method of image processing involves optical techniques by which the image data are processed in a parallel manner.

Digital techniques have advanced rapidly over the past twenty years. Even with the remarkable advances in digital data processing techniques, however, the huge amount of data contained in a high resolution image presents a formidable task for a large digital computer. For example, the two dimensional Fourier transform of an image with a resolution of 1000 elements in each of its two dimensions contains a million points for which the intensity information must be encoded for digital processing. If each point is represented by seven bits (128 amplitude levels) then the computer must handle 7×10^6 bits per image processed. If the discrete Fourier transform of these data is taken directly, the computer must perform a number of operations which is proportional to N^2 where N is the number of elements in each dimension of the image. Using the techniques of efficient computation of the Fourier transform developed by Cooley and Tukey [1-1], the computation time may be reduced to an amount proportional to $2N (\log_2 N)$. This efficient algorithm for the digital computation of the Fourier transform reduces the computation time considerably when N is large. Even so, processing an image with high resolution can require the expenditure of an appreciable amount of computer time. For example, the estimated computation times involved in computing the Fourier transform of an image containing 1024 x 1024 points using the efficient algorithm would be approximately 20 minutes [1-2]. Using the brute force transform would require the better part of a day. These time estimates assume that the computer memory is large enough to store all of the data samples. Either method could hardly be classed as a real time operation.

Optical data processing can produce the Fourier transform of an input image essentially instantaneously. Coherent optical data processing has existed since the early 1950's when many of the early concepts were published [1-3, 1-4, 1-5, 1-6]. Optical data processors in the past have suffered from the techniques used to place into the optical system input images and filter functions. Until recently photographic film was the medium used for this purpose. The processing time required for photographic film produced long delay times between the input image generation and the processing results. Using highly sophisticated processing techniques this time delay could be reduced to minutes.

Recent developments in real time input devices for optical processors have put the optical processor on the verge of real-time operation. Devices such as the General Electric coherent light valve (CLV), the Image Forming Light Modulator (IFLM), a version of which was constructed at Georgia Tech, the Hughes Liquid Crystal Modulator and the Itek Corp., Pockel's Readout Optical Modulator (PROM) are devices which provide the real time input function. These devices have been considered in this investigation as possible candidates for the role of a real time input device.

It was the purpose of this investigation to evaluate the components of an optical processor required to construct an on-board optical processor for use on a spacecraft. The operation of the on-board processor must be real-time or near real-time to provide the processing capability desired. Critical to this mode of operation are the real-time input devices to the optical processor which provide the inputting of images to be processed or which provide the capability of placing various filter functions in the optical processor transform plane. Since these input devices are critical to the operation of the optical processor much of the project effort has gone into the investigation of the characteristics of these devices. The results of this investigation are discussed in Section III. At this time no input device presents a clean-cut choice of being the "best" device for use as an input device. The characteristics of the devices are discussed and observations are made on the applicability of the various devices for use as a real time input device for an on-board processor. Based on the information gathered, the specification of the exact details of an on-board optical processor at this time is premature. Laboratory evaluation of various aspects of the operation of these devices should be carried out before the detailed specifications of an on-board optical processor can be detailed with a reasonable confidence that the device will perform satisfactorily the design objectives.

Since the optical processor input devices cannot be specified at this time, neither can the mechanical and electronic processor components be specified in detail. The sections on the mechanical and electronic design, instead of specifying in detail the configuration of an optical processor, discuss considerations which apply in general to an on-board optical processor. These discussions provide a basis for the detailed design of these two systems once a configuration of the processor is determined.

Digital simulation of an optical processor can provide an insight into the operation of the processor. The detailed simulation of an optical processor would be difficult to implement because of the mass of data contained in the type of images to be processed, and would require the expenditure of a large amount of digital computer time. However, the digital simulation can provide an insight into the operation of an optical processor in performing convolution, and filtering operations. Evaluation of the decay characteristics of image devices may also be carried out. In Section VI a preliminary evaluation of the digital simulation of several operational aspects of an optical processor are described.

In general, what is presented in this report is a review of the status of selected components of an optical processor, a general discussion of the mechanical and electronic considerations of an on-board optical processor, and a preliminary simulation of certain aspects of an optical processor. Recommendations as a result of the study are that the optical processor be set up in the laboratory and that the various devices be evaluated as to their detailed performances as related to the operation of an optical processor before detailed specification of such a processor are specified.

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II. OPTICAL PROCESSORS

The general purpose of this investigation was to specify the general configuration of a coherent optical processor which would be suitable for operation on board a spacecraft. The goal of this application is to relate the on-board optical processor to a specific data processing operation which would allow a reduction in the data transmission requirements of the spacecraft-to-ground data link. To do this would require identification of the portion of the data which could be eliminated by data reduction techniques. Such information for future experiments is difficult to obtain since in many cases the content of the data and the information of value are not known in advance. In some cases it may be desirable to transmit all the data to the ground and then apply data reduction techniques to reduce the data which are transmitted to a specific user. This philosophy, of course, would not allow on-board data compression since the compression algorithm cannot be specified in advance.

In view of the uncertainty connected with a priori specification of the data compression techniques which may be useful for on-board spacecraft data reduction, a general purpose on-board optical processor was selected for this investigation. This processor would be capable of real time spatial filtering and frame-to-frame optical correlation.

At this time several components of a real time optical processor have not progressed to a state of development that would allow their clear-cut selection for a specific application in an on-board optical processor. The most important of these components is the real time optical input device which is required for the input object plane and the spatial frequency plane. Input devices based on liquid crystal technology or the solid state Pockels effect optical modulators are the principal candidates for coherent optical processing, but none had specifications which would make a clear-cut choice for a given processing application. These real time input devices are critical to the success of a real time optical processor and a significant part of this study was devoted to them. These devices are described in detail in Section III of this report.

Because of the wide variation in characteristics of the real time input devices, such as response time and storage time, the detailed specification of the peripheral equipment required to operate such a device cannot be established at this time. Conversion devices for transforming an electronic signal in television format to a coherent optical representation have many demands placed upon them. In some cases the conversion device may be required to furnish enough light intensity during one frame time to excite an optical input device which has storage capabilities. In other cases, because of the response and decay characteristics of the real time input device, the conversion device itself may be required to store the input image over an appropriate time interval, possibly many television frame times.

In view of these considerations a highly flexible configuration providing for frame-to-frame image correlation or spatial filtering has been considered. This configuration, which employs the spatial heterodyne geometry, is shown in Figure 2-1. In this configuration, provision is made for inputting two images I_1 and I_2 into the optical processor. Co-locating the two images in a common input plane allows the optical processor to perform the correlation operation on the two input images. For spatial filtering operations only one input image is supplied to the processor while the desired spatial filter is supplied to a third coherent input device specified as I_3 and located in the transform plane. The two input images can be imaged on the input devices I_1 and I_2 with incoherent light from a cathode ray tube or a storage tube or possibly with coherent light from a scanning laser beam. The images are read with coherent light from an expanded laser beam applied to the input devices through beam splitters S_1 and S_2. Lens L_1 forms the Fourier transform of the input image plane distribution at its back focal plane where the third input device I_3 is placed.

The function of the third input device I_3 is to furnish the proper medium in which the correlation process may take place or to provide the capability of writing a desired filter function to be applied to the transform data. For the correlation procedure the device I_3 must generate the square modulus of the sum of the two input signals. The optical Fourier transform of the square modulus of the two input images I_1 and I_2 results in

I = Incoherent-to-Coherent Imaging Device
S = Beam Splitter
M = Mirror
L = Lens

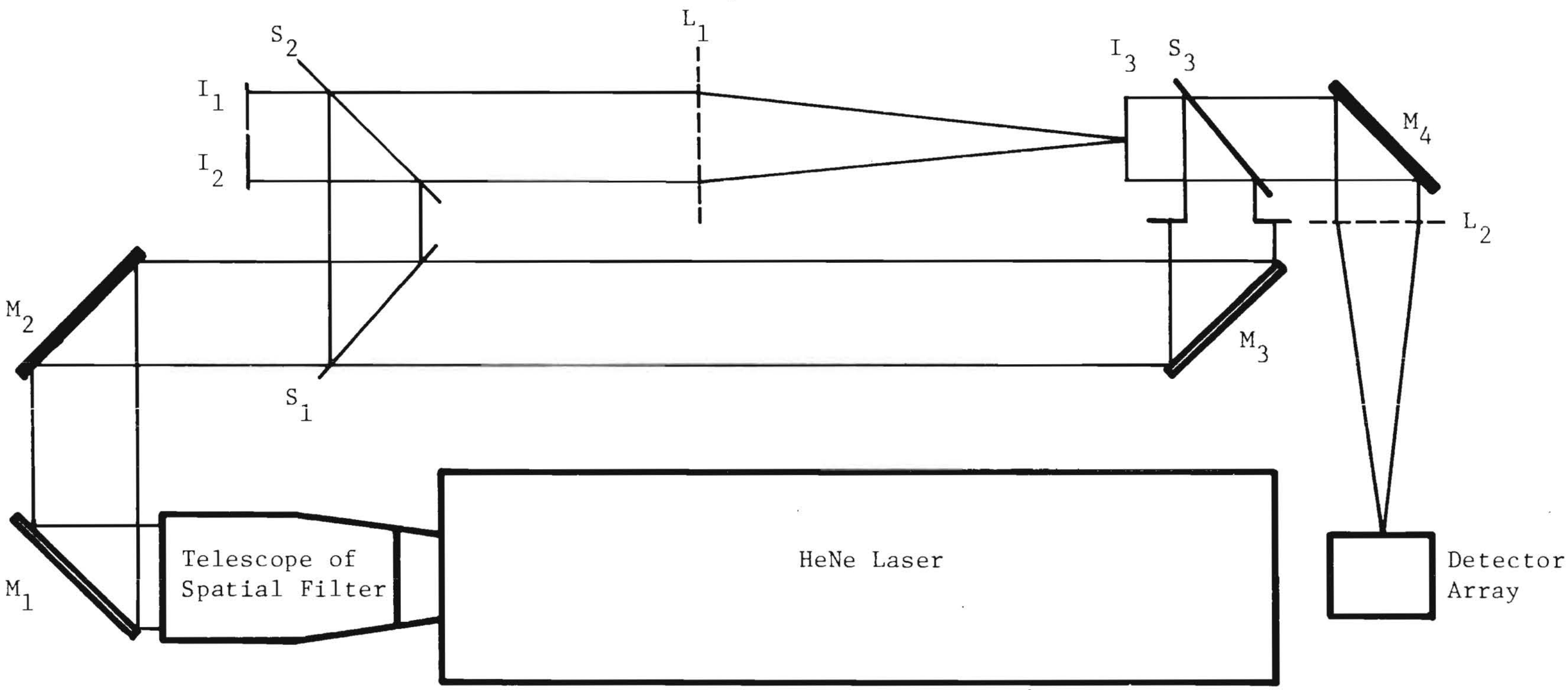


Figure 2-1. Diagram of Optical Processor for Performing Optical Correlation Which Employs Spatial Heterodyne Geometry.

a light distribution which contains the autocorrelation function of the two input images on-axis and the cross-correlation function off-axis by a distance proportional to the separation of the two input images.

The mathematics describing joint transform correlation are given in Section VI.

For spatial filtering two concepts may be applied. For matched filter operation, a linear space invariant filter is said to be matched to the input signal s(x,y) if its impulse response h(x,y) is given by [2-1]

$$h(x,y) = s^*(-x,-y) \tag{2-1}$$

If an input g(x,y) is applied to a filter matched to s(x,y) then the output v(x,y) is found to be

$$v(x,y) = \iint_{-\infty}^{\infty} g(\varepsilon,\eta)\ s^*(\varepsilon-x,\eta-y)\,d\varepsilon\,d\eta \tag{2-2}$$

which is the cross-correlation function of g and s, the two input signals applied to I_1 and I_2 as discussed in the above paragraphs.

Another form of spatial filtering is also used in which the filter function is written on the frequency plane device I_3 as an amplitude mask [2-2]. With this filtering technique simple filter functions are easily realized. A low-pass filter would be represented by a transparent disc centered around the zero frequency or dc component of the transform. A high-pass filter would be an opaque disc centered around the dc component. Various other forms of filters can be implemented in the spatial frequency domain such as band-pass, band-elimination, and directional filters which either pass or stop selected segments of the frequency domain representation of an input signal. All of these frequency domain filter representations are applied as amplitude functions and can be written on the real time image device in the spatial frequency domain, device I_3.

III. OPTICAL CONSIDERATIONS

A. Introduction

Since the coherent optical processor is an analog device, its successful application will be found in special purpose processing systems for which definite advantages over digital computing systems can be demonstrated. For on-board satellite applications, desirable system improvements would include reduction in equipment complexity or power requirements, reduction of RF downlink bandwidth through on-board data compression, and improvements in automatic navigational or docking systems.

The coherent optical processor operates in parallel with the number of parallel channels equal to the number of resolution cells at the input modified by the system modulation transfer function (MTF). A linear transformation can be performed on all these parallel inputs simultaneously; however, the most commonly used input recording medium, photographic film, does not allow real time processing. Even the coherent optical synthetic aperture processors, which employ mono-bath processing techniques, require several minutes between exposure of the film and the useable transparency.

It is clear, therefore, that the most critical component in the coherent optical processor is the real time input device. Over the last five years, a number of devices have been developed around electro-optic crystals, liquid crystal films, ferroelectric ceramics, thermoplastic films, and deformable membranes. On-going development of many of these devices has been stopped because of technical barriers which were too costly to overcome or because of the emergence of other clearly superior device technology.

During the course of this investigation, visits were made to ITEK, Hughes, and General Electric to obtain information on the latest developments in coherent modulator technology, and to observe first hand the performance of the respective devices mentioned above. The impressions gained through these visits supplemented with operating experience on an IFLM which was fabricated at Georgia Tech under contract NAS8-27375 [3-1] form a basis for the information contained herein.

In considering the application of coherent optical processors to on-board spacecraft systems, we will assume that the optical components will be required to satisfy the environmental constraints of spacecraft environment, and that the performance of these components will be compatible with the image quality presently obtained from the ERTS MSS sensor. It has been assumed that optical lens fabrication and coating technology is sufficiently advanced to allow realization of the lens components required for the development of the optical processing systems considered in this report. Hence, the primary emphasis of this study has been directed toward the investigation of real time coherent input devices and detector arrays for sampling and processing the optical processor output plane distribution.

B. Real Time Input Devices

An ideal coherent optical input device would spatially modulate a coherent optical beam to create a phase and amplitude image replica of high resolution and very low distortion which could be instantaneously altered to form new images or stored indefinitely to be used as a permanent image transparency. Practical devices deviate from these ideal characteristics in image quality, time interval required to change the image, and length of time the image can be stored without image degradation. Although some of the devices surveyed exhibited excellent performance in one or perhaps more of the desired characteristics, no device was found to perform well in all categories.

Although this study was not oriented toward a specific spacecraft application, the field of candidate devices can be significantly narrowed by relating potential processing tasks to two common image formats. The ERTS multispectral scanner (MSS) sensor generates a complete image frame consisting of 2313 x 2313 resolution cells at the rate of one image every 28.7 seconds. High resolution vidicons, on the other hand, are capable of generating images with about 1000 x 1000 picture elements at a rate of 30 Hz. We have, therefore, restricted our attention to devices which appear to have the potential for achieving image quality compatible with multispectral scanners and capable of operating at television rates.

The first screening of coherent optical input devices for on-board satellite optical processing applications yielded five potential device technologies. These potential technologies are represented by the ITEK Pockel's Read-Out Optical Modulator (PROM) [3-2, 3-3, 3-4, 3-5], the Hughes Photo-activated Liquid Crystal Light Valve [3-6, 3-7, 3-8, 3-9], the Image Forming Light Modulator (IFLM) [3-1], the General Electric Coherent Light Valve (CLV) [3-10, 3-11] and the CBS Lumatron [3-12]. Of these, the IFLM, CLV and the Lumatron are modified cathode ray tubes, whereas the PROM and the Liquid Crystal Modulator are very compact devices which operate in an open environment. The CRT type modulators have the advantage of simple electronic interface with the image signal representation of the TV sensor. In all three devices, spatial modulation results from an electron charge distribution which is deposited on the crystal by a scanning electrom beam. The IFLM exploits the Pockel's effect in the electro-optic crystal KD*P, while the CLV and Lumatron are phase modulated by surface deformations in thin thermoplastic films.

The IFLM was eliminated from further consideration for this application on the basis of poor image quality, relatively short lifetime, and system complexity. Although the response time of the IFLM is excellent and its operating mode is well suited for the TV sensor, its image quality is barely sufficient for this application. The resolution is limited to about 20 lines/mm because of electric field fringing in the KD*P plate. The current state-of-the-art in crystal technology limits the size of good quality KD*P plates to about 2 inches, which results in a maximum of about 1000 resolution elements along each dimension of the plate. In addition, this resolution can only be achieved if the crystal is cooled to near its Curie point which is about -55° C. The lifetime of the KD*P modulator is also questionable because of the surface degradations associated with the intense electron beam required for full contrast. The lifetime of the electron gun cathode is severely reduced when operated at the required beam current of $2A/cm^2$. These considerations along with the complexity associated with the modulator cooling requirement cause the IFLM device to be rated well below the leading contenders.

The Lumatron solid film thermoplastic modulator was eliminated from consideration because of its slow recycle time. Although good images are possible with this device, a complete write-erase cycle requires several seconds.

C. Review Of Principles Of Operation Of Selected Optical Input Devices

The CLV modulator is based on deformation of an oil film by a charge pattern which is applied by a high resolution electron gun. In the basic light valve configuration, the oil is applied to an optical disc which rotates through a reservoir containing the oil. As shown in Figure 3-1, an on-axis electron gun writes a charge pattern on the oil film, and a coherent beam projected through the device slightly off-axis is diffraction modulated by the deformations in the oil film. The image is retrieved in a Schlieren optical system which blocks the undiffracted component of the coherent beam. An advantage of this system is that the diffraction efficiency can go as high as 25-30 percent whereas the maximum diffraction efficiency of an intensity modulated light signal is about 6.3 percent. The response time of the system depends on the deformation time of the oil film. A time history of the oil film deformation is shown in Figure 3-2. The integration time, which is defined as the time for which the deformation is above 1/e of its maximum value, can be varied from about 4 msec to 300 msec.

The image quality of the CLV is excellent because of its freedom from defects and blemishes. The limiting resolution is compatible with a 1000 x 1000 line TV system; however, thickness variations in the oil film have not permitted diffraction limited performance.

The most serious limitation of the CLV is its lifetime which is currently on the order of 1000 hours. Although projections of 3000-5000 hours have been made, one year's continuous operation in space would require a lifetime on the order of 8,760 hours. In addition to the consideration of short lifetime, the CLV would have to be modified for operation in a zero g environment. The device in its present configuration is also too large, and considerable reduction in size would be required for spacecraft operations. Finally, the current unit cost of this device is $75,000, and no significant reduction in cost is projected without a significant development program.

Both the PROM and the Liquid Crystal Modulator have the potential for excellent image resolution, although the "cosmetic" quality of the images produced by both devices is only marginally acceptable. The cosmetic quality could apparently be improved by current technology if the financial incentives were

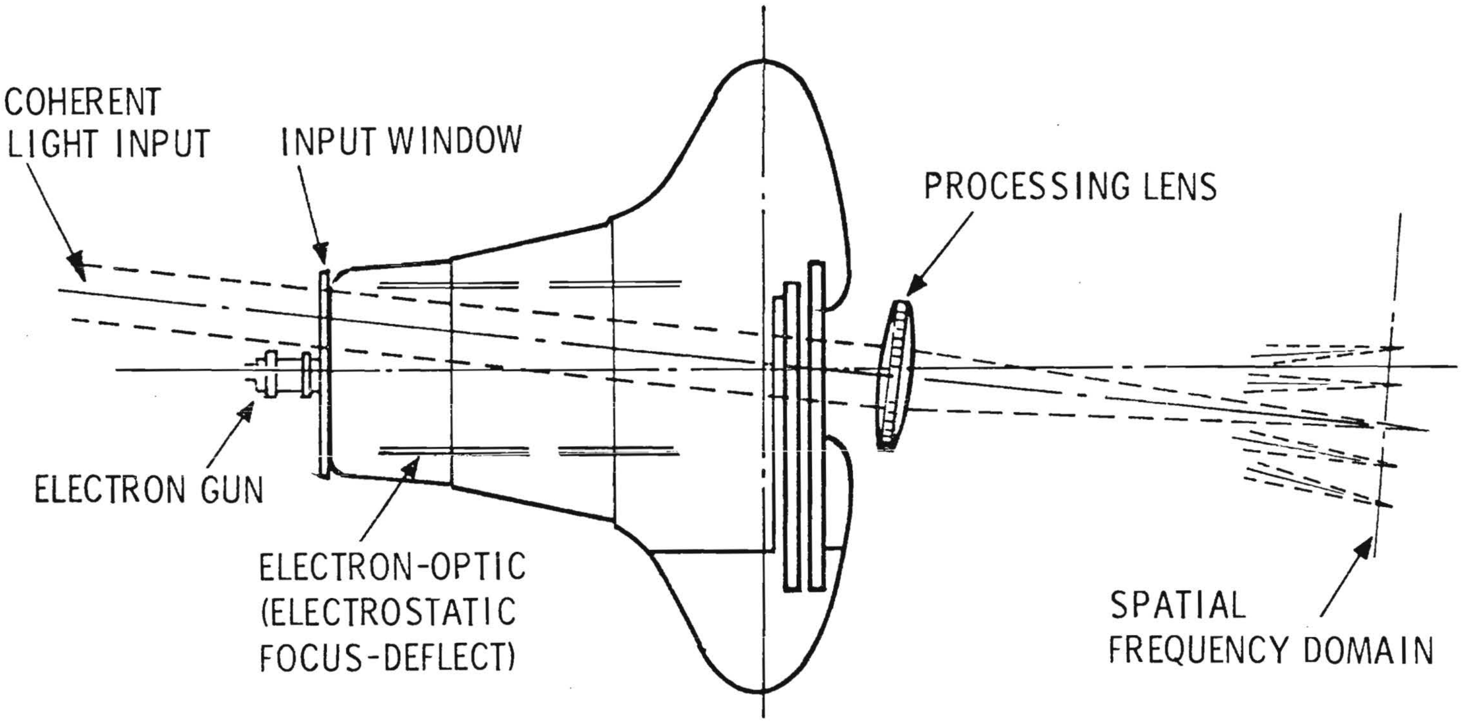


Figure 3-1. A Schematic Representation of the General Electric Coherent Light Valve (CLV). (From Reference 3-11).

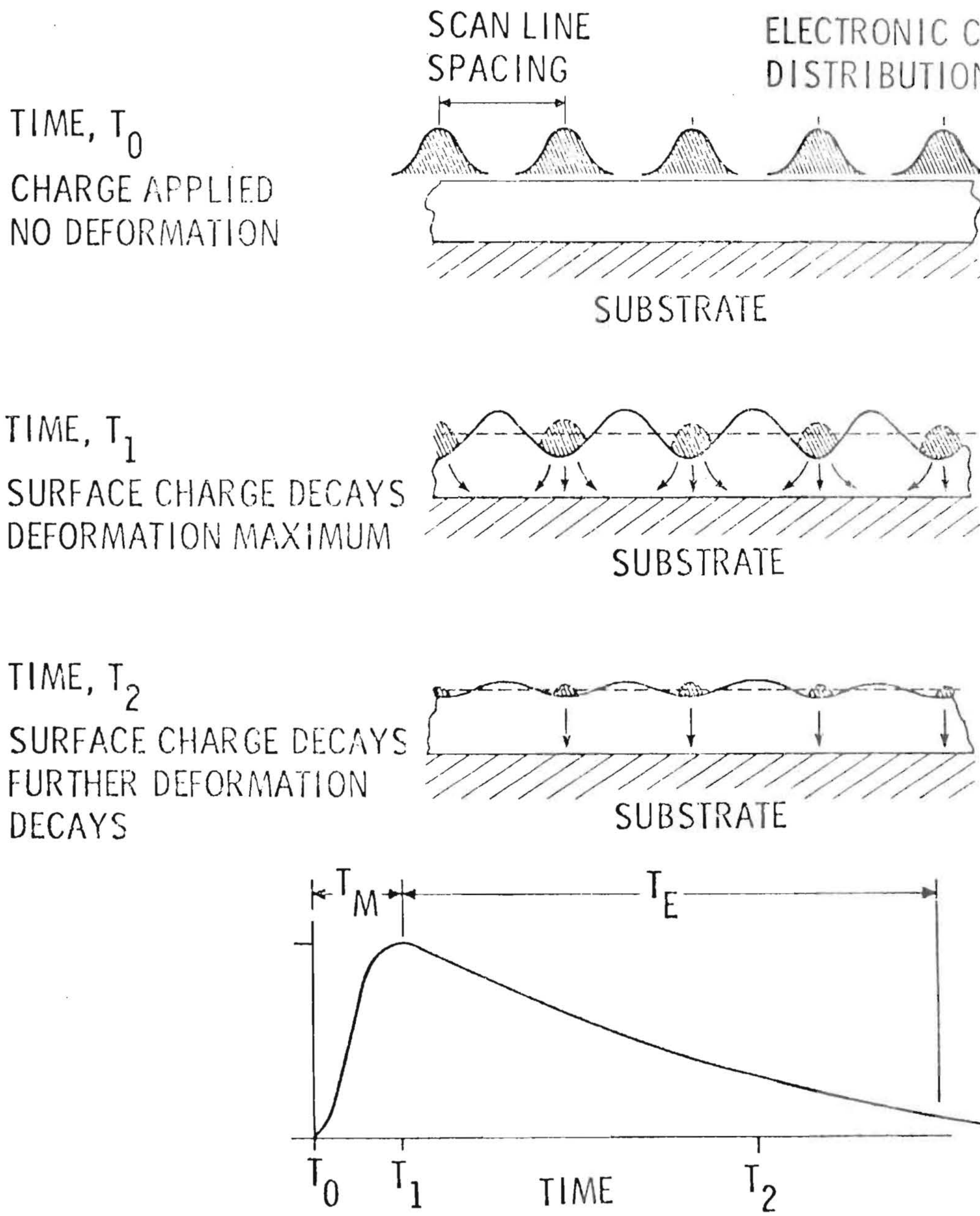


Figure 3-2. Time Dependence of Charge and Deformation on the CLV Writing Fluid. (From Reference 3-11).

present. Unlike the previously discussed devices which operate in a CRT mode with modulation resulting from an electron charge replica of the image, these devices require an incoherent light image as input. Hence, an electrical-to-optical interface is required to establish spatial modulation of a coherent light beam by the desired image.

The attractive aspects of these two devices are their compact size, their potential low cost and high image quality. Although many problems relating to their operational compatibility with the two basic sensors mentioned above remain to be solved, these two devices appear to be the most suitable candidates for on-board spacecraft processing applications. In the discussion that follows, operational considerations will be examined for both devices, and the advantages and disadvantages relating to coherent optical processing will be identified.

The basic principles of operation of the PROM and the Liquid Crystal Modulator will be briefly reviewed as an introduction to the analysis of imaging performance which will follow. The PROM is a solid state device which employs the Pockel's longitudinal electro-optic effect to achieve spatial modulation in a thin plate of bismuth silicon oxide ($Bi_{12}SiO_{20}$). In addition to its electro-optic property, the bismuth silicon oxide (BISOX) crystal is also photoconductive, and the electric field distribution required for Pockel's effect spatial modulation is generated by illuminating the BISOX plate with an incoherent light image. The field is applied across two transparent electrodes which form the outer layers of a sandwich structure containing the BISOX plate whose faces have been optically polished and coated with an insulating layer of parylene. The operating cycle of the PROM is shown in Figure 3-3.

The Hughes Liquid Crystal Modulator is also a sandwich configuration with a thin liquid crystal film and several dielectric and photoconductive layers between transparent electrodes. Because of its thin film construction, the modulator medium is sandwiched between two optically polished glass plates. The Hughes modulator exploits a hybrid field effect mode in which the off-state is controlled by the twisted nematic effect, and the on-state is controlled by the optical birefringence of the liquid crystal. Spatial modulation with this device also requires a light input with the electric field modulation

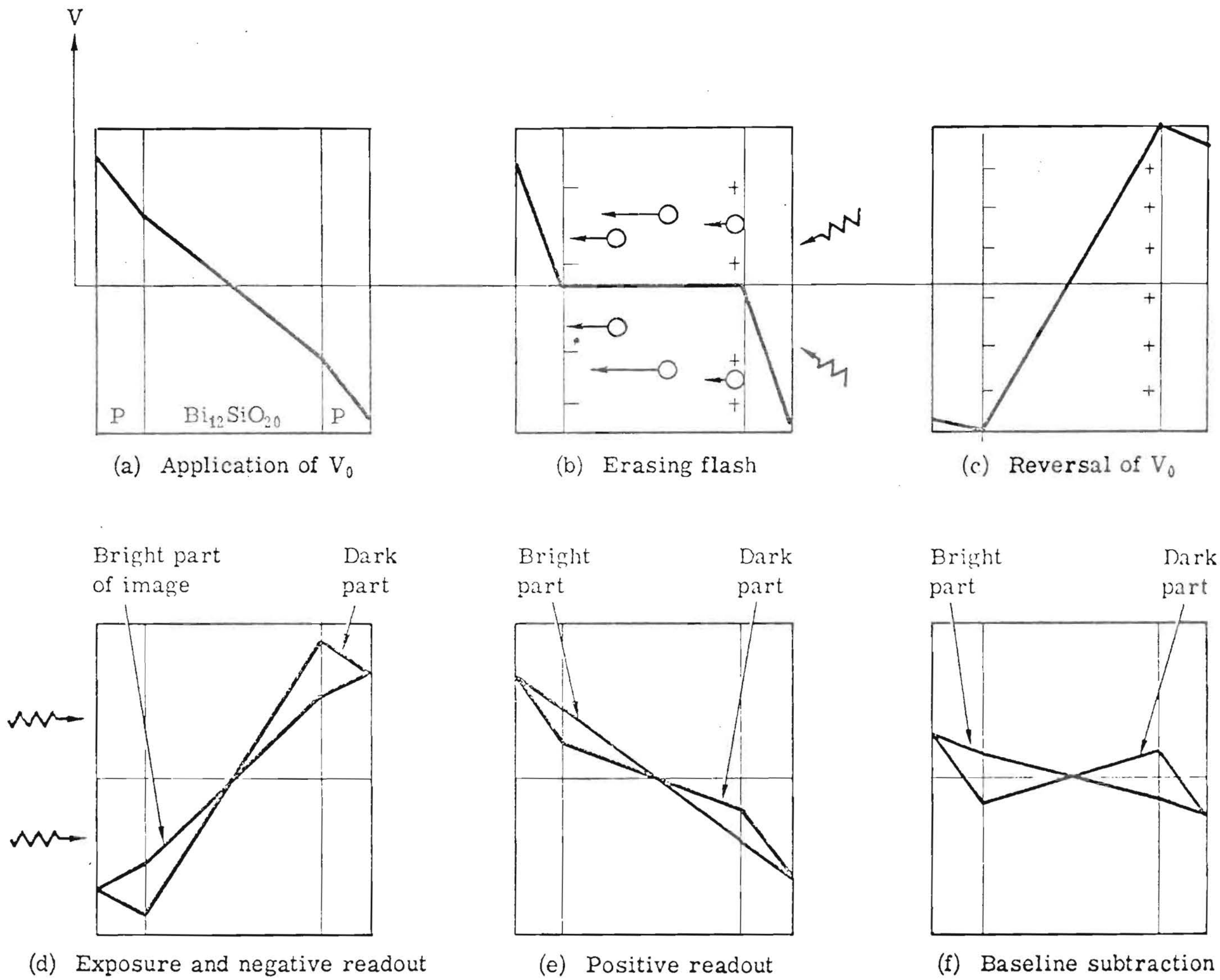


Figure 3-3. Voltage Cycle Used to Operate PROM.
(From Reference 3-5).

resulting from illumination of the photoconductive layer. A cross-section of the Liquid Crystal Modulator is shown in Figure 3-4, and the hybrid field effect is illustrated in Figure 3-5.

An important feature of both the PROM and the Liquid Crystal Modulator is that the contrast can be arbitrarily controlled during the readout cycle by changing the bias voltage across the device. Some interesting possibilities which could exploit this feature are level slicing, contrast reversal, edge enhancement, image subtraction, and reduction of the undiffracted component of the optical Fourier transform. The last feature, suppression of the zero order in a Fourier transform, reduces light scattering effects and detector saturation and also reduces the tendency of the zero order to obscure light diffracted in the low spatial frequency region.

D. Comparison of PROM, CLV, And Liquid Crystal Modulators

A comparison of imaging and system performance characteristics for the PROM, CLV, and Liquid Crystal Modulator is given in Tables III-1 and III-2. The discussion that follows will attempt to point out considerations and trade-offs among these devices which are not evident from these two comparison tables.

A coherent optical spatial modulator can be characterized in terms of its behavior as an optical transparency. Just as photographic film is characterized by its Hurter-Driffield (H&D) curve, the real time optical modulator can be characterized in terms of its transmission-exposure curve. In both cases the input device to a coherent optical processor maps the complex amplitude during exposure into a complex amplitude transmitted into the processor during the read cycle. The transmission-exposure characteristics of the Liquid Crystal Modulator, shown in Figure 3-6a, and of the PROM, shown in Figure 3-6b, are compared to a typical transmission-exposure characteristic for a typical photographic negative transparency in Figure 3-6c.

As was discussed in Section II, it is desirable in coherent optical processing applications for the input device to perform a square-law mapping of the complex exposure amplitude. It is possible with the proper exposure bias to obtain a square-law mapping over a limited dynamic range with photographic

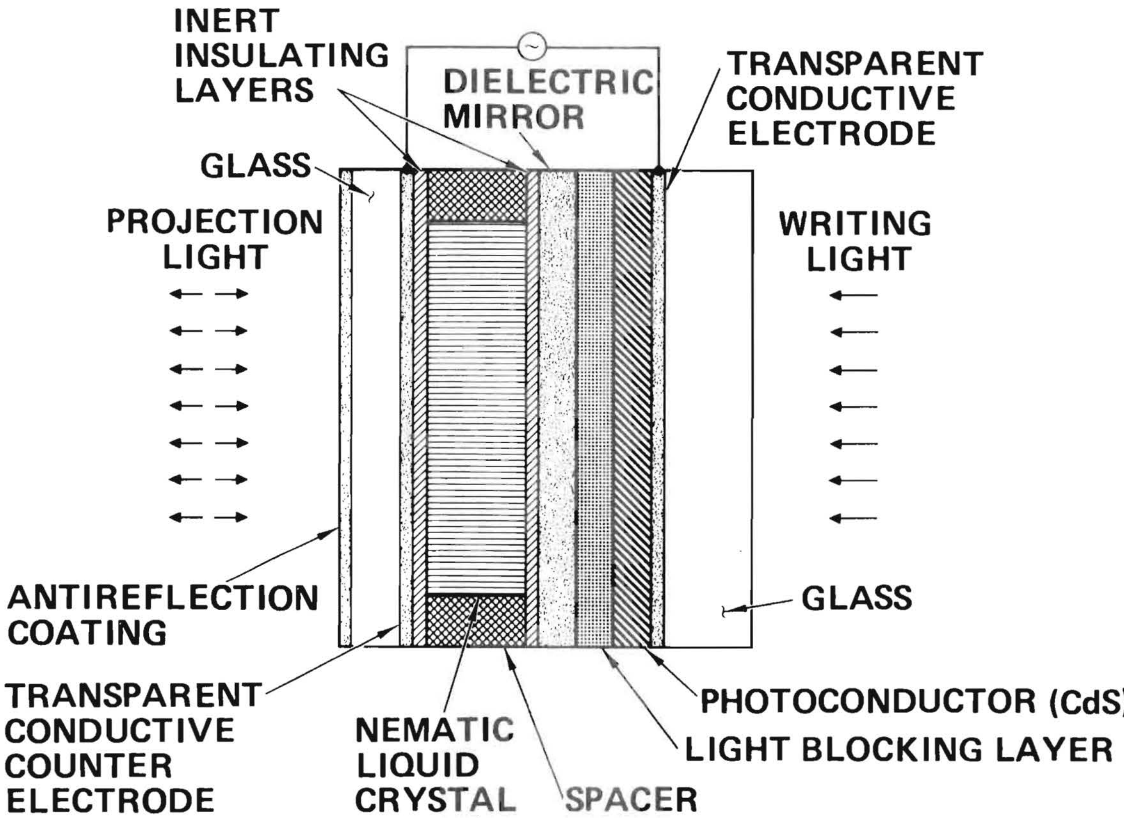


Figure 3-4. Cross Section of the Hughes Liquid Crystal Modulator. (From Reference 3-6).

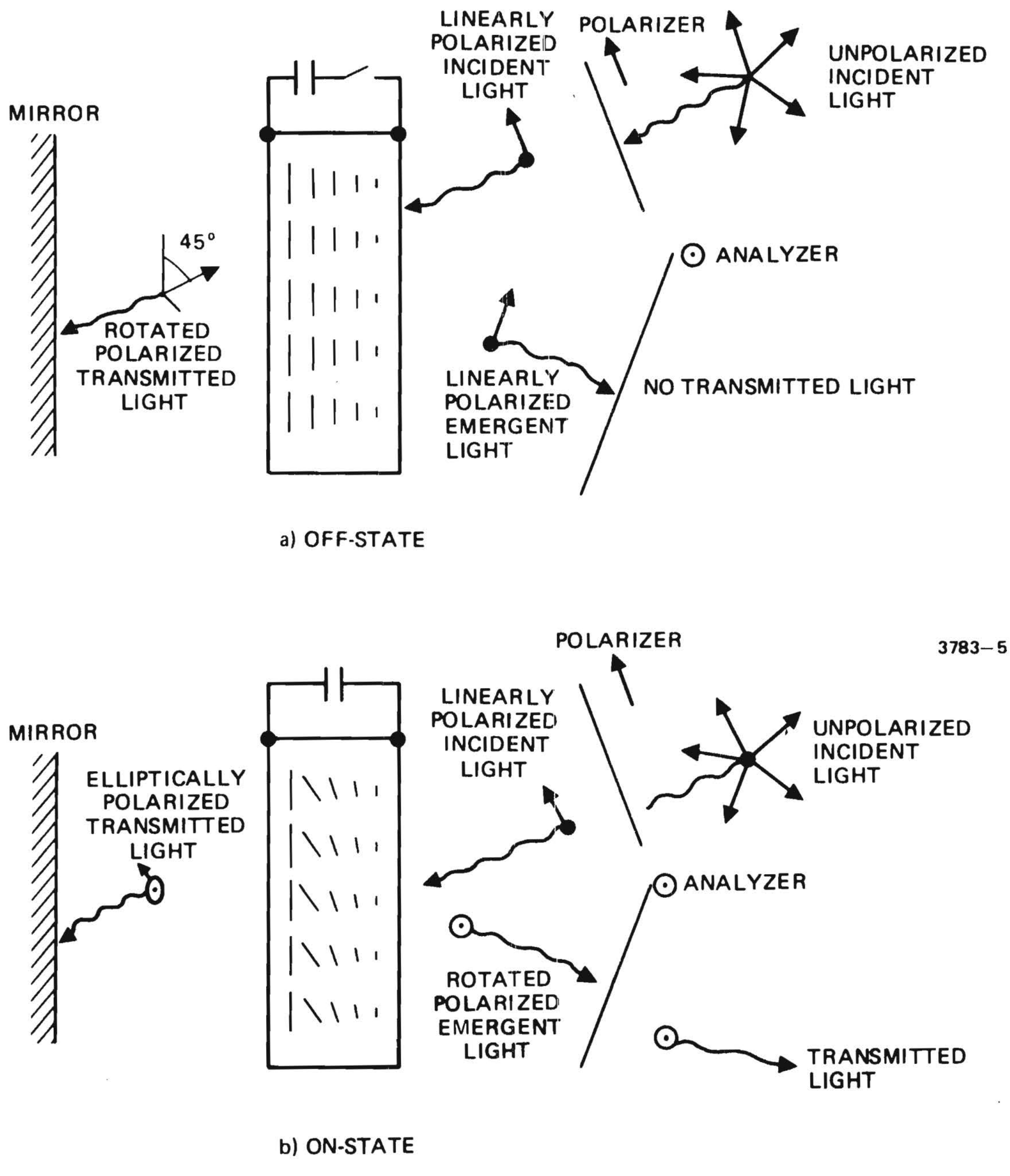


Figure 3-5. Operation of the Hughes Liquid Crystal Modulator in the Hybrid Field Effect Mode. (From Reference 3-6).

TABLE III-I

Comparison of Coherent Image Performance for the PROM, CLV, and Liquid Crystal Modulator

	Photometric Sensitivity	Resolution	Active Area	No. of Resolution Cells	Contrast	Gray Scale No. of Steps for $\Delta D=0.15$	Isolation Read-Write	Input Dynamic Range
GE CLV	N. A.	25 lp/mm @ 50% MTF	1"x1"	625x625 @ 50% MTF	10^5:1	14	∞	21 dB
Itek PROM	300 ergs/cm^2 for C=100:1 10^4 ergs/cm^2 for C=10^4:1	50 lp/mm* @ 50% MTP	1"x1"	1,250x1,250 @ 50% MTF	10^4:1	27	28 dB	40 dB
Hughes Liquid Crystal Modulator	160 μW/cm^2 for C=100:1	60 lp/mm @ 50% MTF	1"x1"	1,500x1,500 @ 50% MTF	10^2:1	9	50 dB	15 dB

* Much greater resolution is possible for images possessing a narrow spatial frequency spectrum.

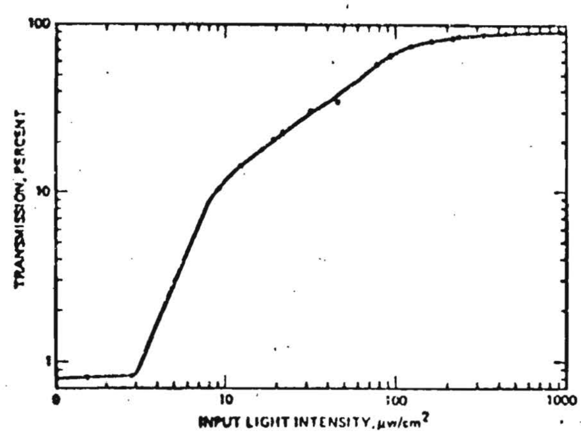
TABLE III-2

Comparison of System Performance Characteristics for the PROM, CLV, and Liquid Crystal Modulator

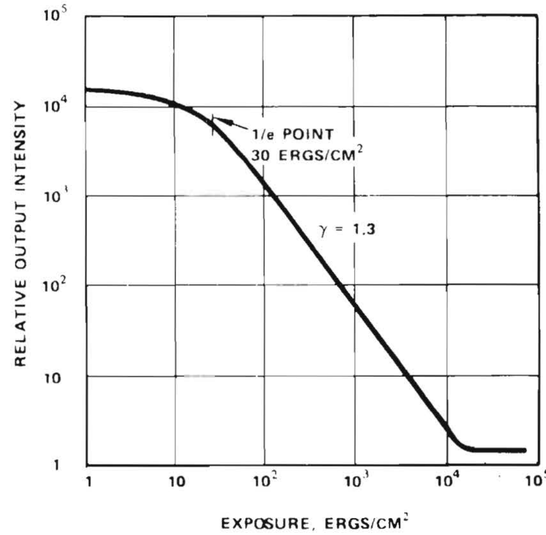
	Response Time	Cycle Rate	Storage Time	Maximum Light Output	Drive Requirements	Lifetime	Level Slicing	Estimated Cost
GE CLV	4 msec.	30 Hz	<300 msec.	700 Lumens	7000 VDC @ 10 μA	1,000 hrs.	No	$75 K
Itek PROM	.01-100 μsec.*	60 Hz	<1 hour†	limited by Read-Write Isolation	2000 Vdc	>10,000 hrs.	Yes	$38 K
Hughes Liquid Crystal Modulator	10-250 msec.*	15 Hz	N. A.	1,000 Lumens	6 Vac @ 0.5 mA	>10,000 hrs.	Yes	$25 K

* Response time is dependent on the writing intensity.

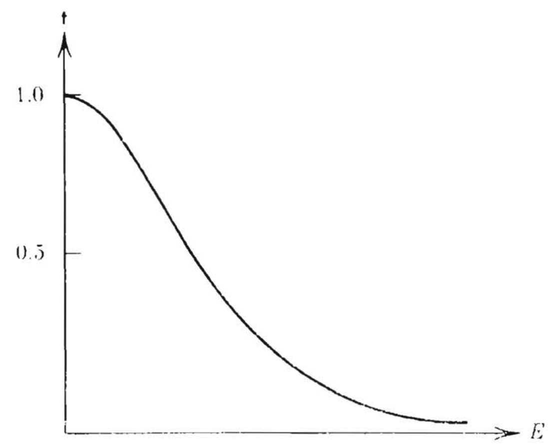
† Maximum storage time cannot be realized for continuous read-out because of image degradation resulting from low read-write isolation.



a. Hughes Liquid Crystal Modulator
(From Reference 3-6).



b. ITEK PROM
(From Reference 3-5).



c. Typical Negative Transparency

Figure 3-6. A Comparison of the Transmission-Exposure Characteristics of Coherent Optical Modulators and Photographic Film.

film of any given exposure characteristics. This characteristic is expressed by

$$\bar{t} \approx t' + A(E - E_b), \tag{3-1}$$

where $\bar{t}$ is the complex amplitude transmittance,

t' is the bias transmittance,

E_b is the bias exposure,

A is the slope of the $t - E$ curve at the bias point,

and E is the exposure defined as the energy per unit area incident on the film.

It would be desirable to establish a square-law operating mode for the PROM and the Liquid Crystal Modulator. An immediate difficulty becomes evident on examination of the transmission-exposure characteristics of the Liquid Crystal Modulator. For this device there is an abrupt reciprocity failure at low intensity levels. That is, further decreases in illumination intensity could not be offset by increasing the exposure time. In addition, and more importantly, the transmission of the Liquid Crystal Modulator is proportional to intensity instead of energy density since it does not integrate the input illumination. A satisfactory theory has not been formulated for the response mechanism of this device, and hence a square-law operating mode would be difficult to specify at this time.

The PROM has a transmission-exposure characteristic which is very similar to that of photographic film, and its electro-optic response mechanism is well understood. The voltage across the crystal due to the photoconductive response of the BISOX crystal is given by

$$V_c \approx V_o e^{-E/E_o}, \tag{3-2}$$

where V_c is the voltage across the crystal for exposure E,

V_o is the voltage for no exposure, and

E_o is the exposure for 1/e response.

For small exposures,

$$V_e \approx V_o(1 - E/E_o), \tag{3-3}$$

and the transmittance due to the Pockel's electro-optic effect for small exposures is given by

$$t = \sin\left[\frac{\pi V_c}{V_n}\right] \tag{3-4}$$

$$= \sin\left[\frac{\pi V_o}{V_n}(1 - E/E_o)\right],$$

$$\approx \frac{\pi V_o}{V_n}(1 - E/E_o),$$

where V_n is the half-wave voltage for the Pockels effect in BISOX.

Thus for $E < E_o$ and $V_c < V_n$, the PROM can be made to respond with a square-law characteristic.

Before leaving the discussion of exposure characteristics, some of the imaging parameters listed in Table III-1 will be defined. The dynamic range is defined as the range of input exposure over which the output intensity smoothly changes. The contrast ratio is defined as the ratio of maximum transmittance to minimum transmittance. A related parameter which was not discussed is the Fourier plane signal-to-noise ratio which is the ratio of signal intensity to background intensity in a Fourier transform diffraction pattern. This parameter is a function of spatial frequency and is an indication of the amount of light scattered by optical imperfections within the device.

The gray scale is defined in terms of the number of equal density steps of the input exposure which can be mapped into changes in transmittance. The number of steps, n, is

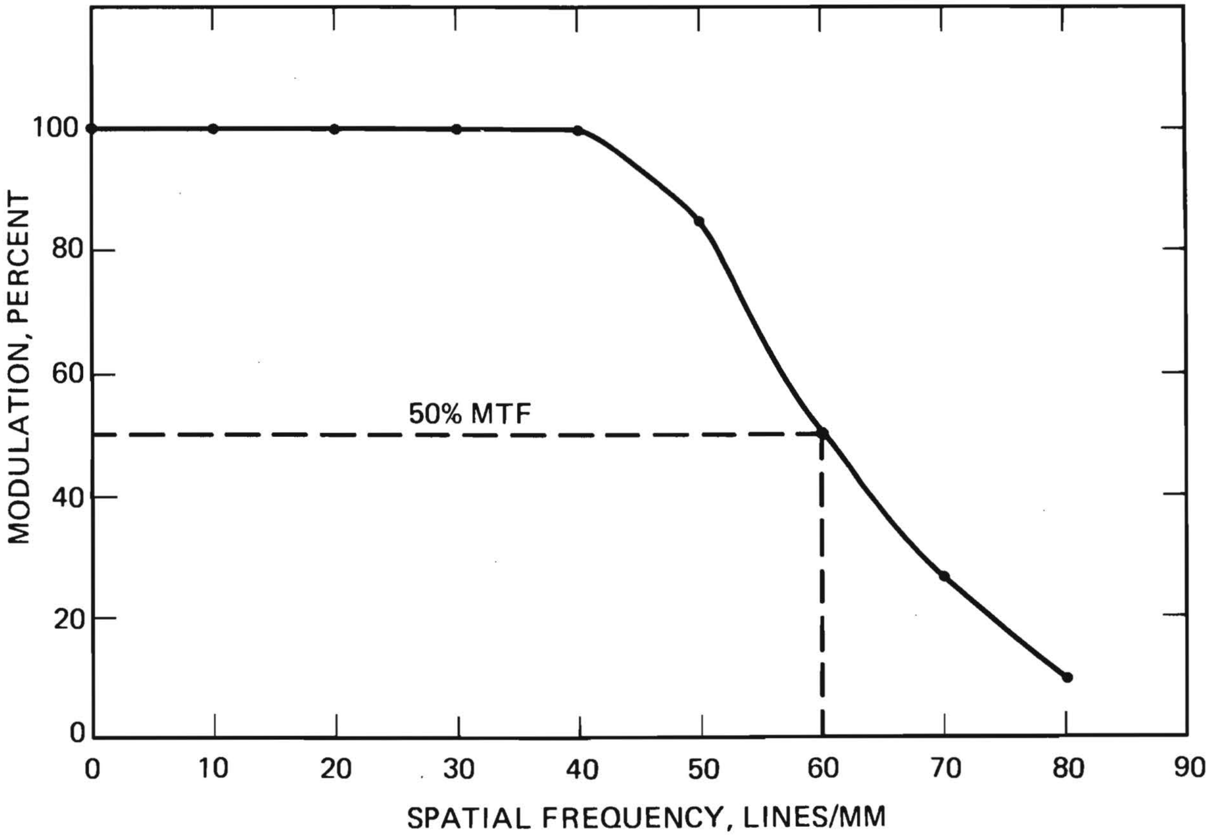
$$N = \frac{\text{Input Dynamic Range}}{\Delta D} \qquad (3\text{-}5)$$

The data of Table III-1 are based on $\Delta D = 0.15$.

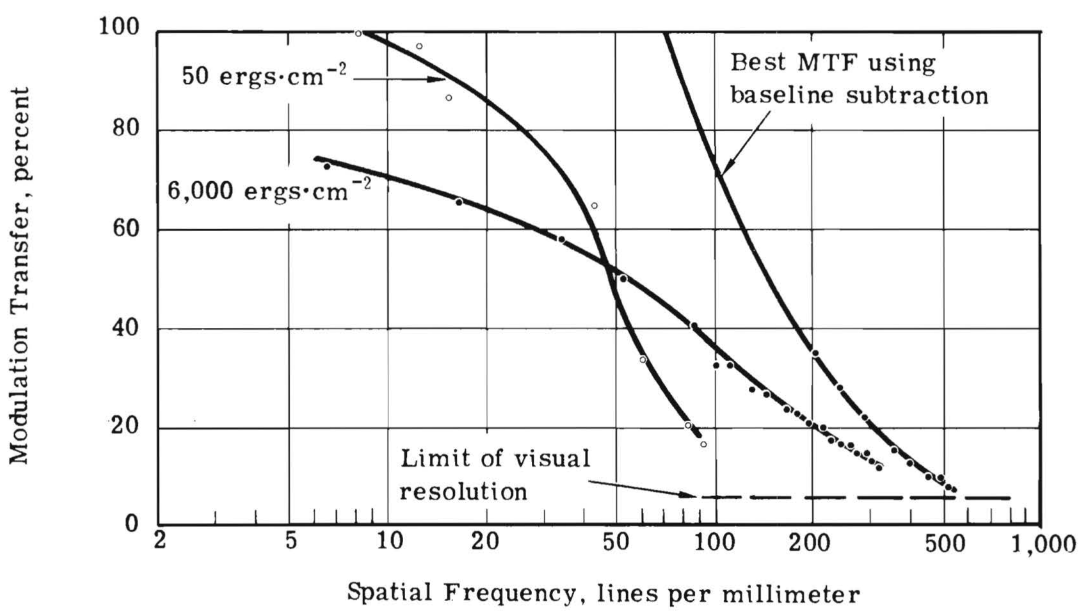
The resolution of the candidate devices has been given in terms of the number of line pairs for MTF = 0.5. Figure 3-7 shows the resolution versus MTF for the PROM and the Liquid Crystal Modulator. Note that very high resolution can be obtained for the PROM using contrast reversal techniques to suppress the zero order of the diffracted light distribution. This mode of operation might effectively increase the resolution for some special purpose optical processing application. It should be noted, however, that only one spatial frequency can be optimized at a time, and since most images have a continuous spatial frequency spectrum, a certain amount of distortion would result.

Isolation between the read-in and read-out operations is required for good image quality. An image stored during read-in should not degrade during read-out to the optical processor, and none of the read-in light should be allowed to leak into the optical processor. Isolation in the Liquid Crystal Modulator is established by a light blocking layer and a wavelength dependent dielectric mirror. This device is capable of isolation exceeding 50 dB, and no performance degradation is anticipated. The PROM, on the other hand, achieves isolation through separation of the spectral response characteristics of its bulk photoconductive and electro-optic effects. The photoconductive response peaks at about 440 nm, and the read-out is usually accomplished with a HeNe laser at 633 nm where the response is down by about a factor of about 400. The maximum readout energy for 1/e response at 633 nm is about 10^4 ergs/cm^2. It is interesting to calculate the maximum CW laser power which can be used to read an image out of the PROM as a function of read-out exposure time for the maximum read-out energy density limitation. This calculation is shown in Figure 3-8. Continuous read-out with a 50 mW HeNe laser, for example, will significantly degrade the image over an exposure interval of about 1 sec. Thus, the storage capability of the PROM cannot be realized if appreciable read-out is required during the storage interval.

The discussion of image quality will be completed by considering



a. Hughes Liquid Crystal Modulator.
(From Reference 3-6).



b. ITEK PROM
(From Reference 3-5).

Figure 3-7. Resolution Performance of the ITEK PROM and the Hughes Liquid Crystal Light Modulator

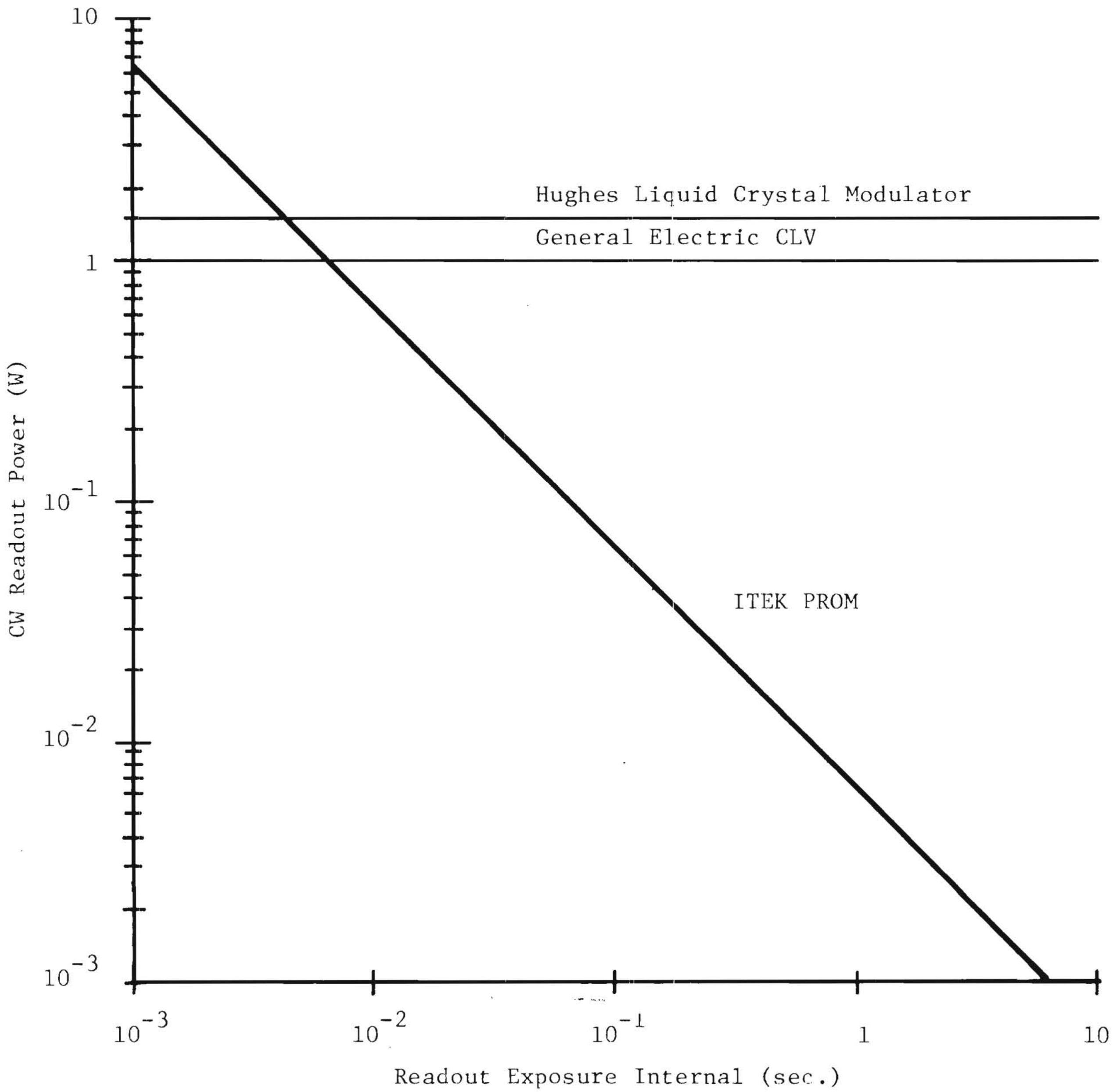


Figure 3-8. Maximum Readout Exposure Interval for 1/e Degradation of a Image Stored on the PROM.

cosmetic defects and wavefront distortion inherent to the candidate coherent optical modulators. The primary sources of image degradation in the PROM are wavefront distortion and point scattering resulting from crystal defects, problems with optical flatness and surface polish, and piezoelectric bending. Currently, the reflection mode PROM achieves $\lambda/4$ curvature with low light scattering. Wavefront deviations can be corrected holographically for a specific device yielding near diffraction limited performance. A far more serious problem is piezoelectric bending which is somewhat dependent on exposure level and affects only the reflection mode device. The best solution to date has been to mount the transmission mode PROM to a dichroic mirror with viscous oil for reflection readout.

Wavefront curvature is also a problem with the Liquid Crystal Modulator because of the surface distortion resulting from edge clamping of the two optical flats; however, point defects appear to be a far more serious problem in the thin film structure of the Liquid Crystal Modulator than in the solid state PROM. The most noticeable point defects result from the sputtered CdS photoconductive film and the amorphous sputtered SiO_2 film which is required for proper alignment of the liquid crystal film. In addition to increasing the background in the Fourier transform plane, point defects which extend to the dielectric mirrors can result in premature device failure through electrochemical degradation of the mirror. These defects presumably can be overcome by applying existing thin film technology and production line processing techniques.

Considerable bowing of the substrate arises during the sputter and evaporation of the many thin film layers of the Liquid Crystal Modulator. Compensation by spherical polishing of the substrate has reduced the wavefront curvature from about $3\lambda/2$ to $\lambda/4$, and the future goal is about $\lambda/8$. Surface warping caused by clamping the sample holder must be eliminated to realize $\lambda/8$ curvature. A cell holder providing for "tuning" of the liquid crystal thickness has resulted in $\lambda/4$ curvature.

While some of the system parameters relating to an electrical-to-optical interface have been discussed in detail in Section V, additional comments will be made in this Section. It is clear that the CLV is the most compatible device for operation with TV image sensors. Both the PROM and the Liquid Crystal Modulator require an optical image as input necessitating an electrical-to-optical interface. However, for an MSS type sensor the CLV has no clear-cut advantage since the MSS output signal is not in a TV video format and a scan converter interface would be required. Although the read-write-erase cycle for the candidate devices is radically different, both the CLV and the PROM are capable of operation at a 30 Hz frame rate. Of the three devices, only the PROM has a controllable erase mode. The Liquid Crystal Modulator does not appear to be capable of operation at 30 Hz in its present configuration. The cycling problem is twofold. First, the response time is a strong function of illumination intensity, and varies from about 10 msec to 250 msec over the dynamic exposure range. This variation is shown in Figure 3-9. Assuming that an image can be stored in the electrical-to-optical interface, (e.g. a storage CRT) Figure 3-9 shows that exposure over a 33 msec interval, corresponding to a 30 Hz frame rate, would restrict the dynamic range of the input to about 4.3 dB (60 to 160 W/cm^2) resulting in only 3 gray scale steps. Second, since the decay time is about 30 msec and independent of illumination intensity, operation of this device at a rate of 15 Hz would be required for complete image decay, and for this cycle rate the input dynamic range would be approximate 7.3 dB resulting in about 5 gray scale steps.

E. Summary of Optical Input Device Chacteristics

In summary, the final choice of a coherent optical input device for on-board spacecraft data processing applications will be strongly influenced by the type of image sensor employed and the processing operations required for the application. In general, the PROM and Liquid Crystal Modulator appear to offer greater potential for spacecraft applications because of their good image quality, compact size, and long lifetime. The CLV, on the other hand, has lower complexity interface requirements, and exhibited the highest image quality of the three candidates. Its poor lifetime, large size and questionable adaptability to a space environment form the primary basis for ranking the CLV behind the PROM and the Liquid Crystal Modulator. A summary of considerations relating to the selection of the PROM or the Liquid Crystal

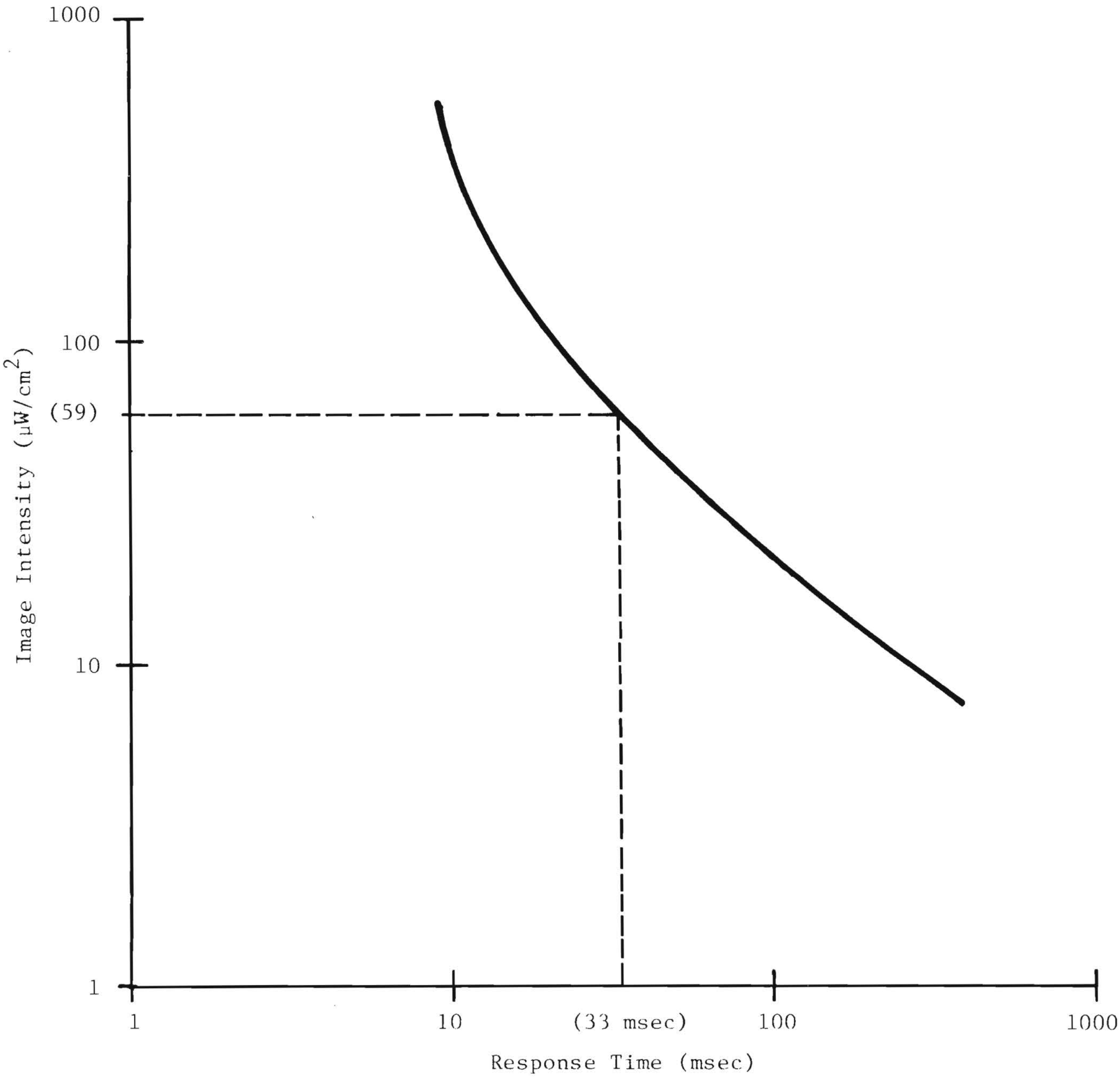


Figure 3-9. Response Time Characteristics for the Hughes Liquid Crystal Modulator.

Modulator for a given optical processing application are presented below.

ITEK PROM

Advantages

1. Compact Size
2. Good Image Quality (High Resolution, High Contrast, High Input Dynamic Range
3. Compatible with TV Sensor
4. Has Storage Capability
5. High Sensitivity
6. Has Level Slicing Capability
7. Controllable Image Erase Capability

Disadvantages

1. Requires High Voltage Supply for Operation
2. Low Read-Write Isolation
3. Long Range Improvements Depend Primarily on Developing New Electro-Optic Crystals
4. Requires Electrical-to-Optical Interface

Hughes Liquid Crystal Modulator

Advantages

1. Compact Size
2. High Resolution
3. Low Drive Power Requirements
4. Potentially a Low Cost Device
5. High Read-Write Isolation
6. Has Level Slicing Capability
7. Long Range Improvements Depends Primarily on Well Established Thin Film Technology

Disadvantages

1. Low Contrast and Input Dynamic Range
2. Slow Response and Decay Times
3. Cosmetic Quality of Images is Poor
4. Alignment of Liquid Crystal Film can be Destroyed by Mechanical Shock

F. Correlation-Plane Detector Requirements

There are specific requirements for the physical characteristics of a detector to be used in the correlation plane of an optical processing system. These requirements are described here and a discussion of detector characteristics follows. The correlation plane requirements are then compared with available detector characteristics.

The information in the correlation plane is in the form of a spatial distribution of light intensity. The detector should therefore sample at discrete points or scan the area covered by this distribution. For example, the use of an array of discrete elements, the outputs of which can be electronically scanned, enables near real-time processing to be achieved. This mode of operation would be virtually impossible to accomplish by physically scanning the light distribution with a single detector element. Even with electronic scanning of a fixed array, the response time of the detectors must be minimized.

The light intensity can vary large amounts over small distances. Therefore, detector elements with a wide dynamic range and small size are required. Likewise, the intensity patterns of interest may vary by relatively small amounts over large distances. This possibility requires highly stable detectors with a wide dynamic range.

With a laser as the source in an optical processing system there is usually more than enough power available to saturate the detector elements in the high intensity regions of the information plane. However, some incoherent-to-coherent input devices are capable of contrast reversal operations which can be employed to reduce the undiffracted component of the Fourier transform diffraction pattern by a factor of 10^4. In this case, the dynamic range requirements are greatly reduced. The major consideration is then a lack of adequate sensitivity in the regions of low light level. In summary, the requirements for a correlation plane detector are that it consists of an array of very sensitive, highly stable, and fast detector elements that respond linearly with irradiance over a wide dynamic range. The arrays must be capable of being fabricated in a variety of sizes and configurations with adequate resolution for the optical data processing application.

G. Available Detector Arrays

The most promising detectors for use in the correlation plane of an optical processing system are the solid state devices of the following types:

1. Photodiode arrays,
2. FET bucket brigade,
3. Charge coupled devices (CCD's), and
4. Charge Injection Devices (CID's)

Each of these will be discussed separately before a comparison of the advantages and disadvantages of all of them is made.

1. Photodiode Arrays

Photodiode arrays are currently available in either polar or rectangular formats.

A polar-format detector array, commercially available from Recognition Systems, Inc. (RSI) [3-13], consists of 32 wedge-shaped elements of uniform size on half the circular area of the array. The other half consists of 32 concentric semicircular ring-shaped elements. This detector was designed to measure the spatial distribution of energy in Fraunhofer diffraction patterns. The wedge-shaped elements integrate the energy with respect to radial direction to yield a measure of the distribution of energy as a function of angle around half the pattern. The ring-shaped elements integrate with respect to angle and measure the distribution of energy as a function of radius around the other half of the pattern. The area of the center ring element is the smallest. The area of each succeeding ring element is larger. This increase in light detection area with radius partially compensates for the usual decrease in light intensity with radius.

The 64 elements of the array can be read out either serially or in parallel at rates to 200K elements/sec. Recognition Systems sells a variety of electronic systems ranging from manually switched single amplifier readout units to systems consisting of individual chopper stabilized preamplifiers, sample-and-hold circuits, and auto-ranging amplifiers followed by high speed analog-to-digital converters.

The auto-ranging amplifiers are useful for applications requiring a wide dynamic range. The dynamic range of a silicon PIN photodiode can easily cover 6 decades, and, with care, can be extended to eight or nine decades. However, even low level reflections from antireflection-coated optics within an optical processing system can limit the useable dynamic range. An electronic system with 20 octaves (6 decades) dynamic range can be purchased from Recognition Systems.

As mentioned above, even small amounts of reflected light can limit the dynamic range of the optical signal. For example, the detector itself can reflect some light back toward the optical system. A small fraction of this light might then be reflected by a lens or other device back to the detector on an otherwise unilluminated element of the array.

For uncoated optics, the power reflection coefficient for normal incidence on an air-glass interface is about four percent. The reflection coefficient for light scattered in an optical system between lenses could, therefore, be as high as 1.6×10^{-3} along the primary direction. Thus, the measured range of the signal will be lower than the actual dynamic range without reflections.

Two modifications of the RSI detector array should be tested for dynamic range improvement. One is to drill a hole through the center element of the detector array to allow the intense undiffracted component of the optical transform to pass through and be collected by a separate PIN photodiode. This separate detector could be cocked at a slight angle such that any light reflected from it would not pass back through the hole in the detector array. Light reflected onto the back of the detector would not re-enter the lens system and hence would not affect the measured light pattern.

A second possible modification would consist of an antireflection (AR) coating on the window faces of the photodiode array. This would reduce the amount of light reflected by the detector array since the standard detectors from RSI are not AR coated. This modification could be used in conjunction with the small center hole which would transmit the undiffracted light component. In addition to these suggested modifications, RSI has proposed to eliminate the glass window and apply a protective coating to the surface of the silicon array. This modification is not, however, available at this time.

Rectangular-format photodiode arrays are available from Reticon Corporation.

The silicon chip on which the array is fabricated also contains MOS multiplex switches and an MOS shift register for scanning. The array and electronic scanner are included in a single integrated circuit type package. Thus these devices are self scanning, and the output signal consists of a series of charge pulses proportional to the light intensity on the corresponding photodiodes.

Self scanning photodiode linear arrays can be fabricated with smaller center-to-center spacing between elements than square arrays because of the space required for the interconnecting lines. The smallest center-to-center spacing for linear arrays has been 1 mil, and for square arrays it has been 4 mils. Thus the spatial resolution for the square arrays is poorer than for the linear arrays.

In the charge storage mode of operation the capacitance associated with each photodiode is charged to a common potential through the video line as each diode is addressed by the shift register. An amount of charge proportional to the light intensity integrated over the scan period is drained from the capacitance associated with each photodiode. The amount of charge drained from each diode is read out sequentially on the next scan when the charge is replaced.

The scan rate can be varied to obtain the best combination of sensitivity and speed. If the scan rate is lowered, the effective sensitivity is increased because the integration time is increased. However, changes in light intensity that occur faster than the span period cannot be observed. So, the scan rate should be optimized for each particular application.

2. FET Bucket Brigade

The "bucket brigade" detector array utilizes FET production techniques that have been refined to a high degree [3-14]. The term "bucket brigade" refers to the way the signal charges are transferred from one sensor element to the next in the scanning process. By transferring the charge in this way, some of the connecting lines required by the self scanning photodiode array are eliminated. This allows closer spacing of the sensitive elements of the bucket brigade array, and thus better resolution than has been achieved with photodiode arrays.

3. Charge Coupled Devices

Several companies are active in the development of Charge Coupled Devices (CCD's), and there are applications other than image detecting. The operation of CCD's is similar to that of the previously described bucket brigade devices. That is, an array of sensitive elements generates a charge proportional to the amount of incident light, and the charges are read out at a single terminal by transferring the charge packets from one element to the next in line.

CCD's employ an array of capacitors fabricated on a single-crystal wafer while, as indicated earlier, the bucket brigade devices utilize an array of FET's. Even though the two devices are similar in operation, there are advantages and disadvantages characteristic of each one due to the different technologies used.

The spacing between electrodes in a single layer has been reduced to about 2 μm, and Bell Labs had developed a multilayer technique which reduces the spacing to essentially zero.

Transfer efficiencies greater than 99.996% have been measured for linear CCD arrays. High transfer efficiency is required where the number of elements in an array is large. A principal objection to the bucket brigade devices compared with CCD's is that the charge transfer efficiency is only 99.990%.

Compared with the self-scanned photodiode arrays described earlier at least two advantages of CCD's can be seen. The first is the resolution achievable with CCD's. The spacing between CCD elements has been reduced to zero while that of the self-scanned photodiode arrays is about 4 mils or 100 μm. A second advantage of CCD's is the wider dynamic range achievable. CCD's exhibit a dynamic range of about 1,000 compared with a dynamic range of 100 for the self scanned photodiode arrays, however, the external electronics for driving the photodiode arrays is simpler than that for CCD's. Also, there is no charge spill-over in the photodiode devices as there is in CCD's. Charge spill-over produces blooming in CCD's. Techniques for reducing the blooming are being developed but have not been perfected.

Typical defects in the photodiode arrays affect only a single element, or a point in a square array. In CCD's, however, line defects occur because of the way the charge packets are transferred through each line of detector elements.

The peristaltic CCD was developed in an attempt to increase the clock rate capability of CCD's. 100 MHz shiftout rates have been achieved with this device.

4. Charge Injection Devices

General Electric's charge injection devices (CID's) are similar to CCD's in that MOS fabrication techniques are utilized and that the spatial resolution obtained is high. The basic difference is in the way the photon-generated charge packets are read out. The CID consists of capacitors in an X-Y addressed array [3-15]. The charge in each element is injected into the substrate and measured either at the substrate or at the addressed array line. The latter method yields better results.

Some advantages of CID's are:

1. More tolerance to processing defects,
2. Avoidance of accumulated charge transfer losses, and
3. Minimized blooming.

Because of the X-Y addressing, a defect in one element does not affect the output from other elements. Therefore, the defects show up in the image as points rather than as line defects. Another advantage of the X-Y addressing format is that it allows a random access capability which can be utilized for electronic zooming. Each element can be read out in less than 100 msec.

The sensitive area of each element can be larger than the electrodes. As a result the CID utilizes about 90% of the available silicon area. For a given number of elements in the self-scanned photodiode arrays three to four times the silicon area required by the active elements is required by the whole array in order to accomodate all the connecting lines.

H. Comparison of Correlation Plane Detectors

Table III-3 presents a comparison of the correlation plane detection devices discussed.

TABLE III-3

TYPICAL PARAMETERS FOR ARRAY DETECTORS

Device	Array Configuration	Element Spacing	Illumination Sensitivity	Dynamic Range	Response Time	Frame Rate	Random Access
Reticon	Linear and Rectangular -Self Scanning Photodiode Array	linear- 1 mil rect.- 4 mil	$2x10^{-3}$ ft. cd.	30 dB	1 μsec.	1 kHz	No
RSI	Polar Photodiode Array	1 mil	<1 $\mu W/cm^2$	60 dB	<1 μsec.	6.3 kHz	Yes
Bucket Brigade	Rectangular	3 mil	1 ft. cd.	18 dB	10 μsec.	60 Hz	No
CCD	Rectangular	2 μm	<10 ft. cd.	30 dB	1 μsec.	<1 kHz	No
CID	Rectangular	3 mil	0.1 ft. cd.	20 dB	<0.3 μsec.	30 Hz	Yes

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IV. MECHANICAL CONSIDERATIONS

A. Mechanical Design Requirements

Construction of a space-qualified optical processor will require careful attention to the mechanical design. The accuracy and stability of inter-element spacing and alignment of optical components may necessitate dimensional stabilities of the order of one wavelength of visible light. Such precision can be difficult to achieve even in laboratory environments.

Many important aspects of the mechanical design of a processor can be undertaken only after the particular optical design is fixed. Since a particular processor design was not accomplished in this study, a detailed mechanical design could not be accomplished. However, some of the more important considerations can and will be discussed in the following sections, and the method of applying these will be illustrated using an assumed processor design as an example.

B. Flight Environment

1. Overview

An optical processor on board a spacecraft will be subject to a relatively hostile environment compared to that of a laboratory processor. Stresses will occur due to two sources of loading, mechanically induced and thermally induced. The processor structure must withstand these stresses and maintain the dimensional stability required for the optical function.

Mechanical stresses (due to acceleration, shock, vibration, acoustic pressures, etc.) will be at a maximum during launch operations. Once the spacecraft achieves orbit, the system should be relatively free of mechanical loadings unless spacecraft maneuvers are undertaken. Since optical processors will not be required to operate during the launch phase, it is not necessary for the design to maintain component spacing comparable to optical wavelengths during the periods of severe mechanical loadings associated with launch. The launch induced loadings must be considered in the design, however, to insure that permanent deformation does not occur.

Thermal stresses due to temperature changes must also be considered in the design as these stresses can affect the dimensional stability of the processor. There are three sources of thermal loadings that must be considered. These are (1) solar heating, (2) internal heating due to processor operation and (3) external heating from other spacecraft systems.

Temperature changes can cause high thermal stresses when materials of widely different thermal coefficients of expansion are joined. These stresses can produce excessive distortion of the mechanism. To eliminate this effect, all major structural components should be made of the same (or thermally similar) material.

Even with the processor made of a single material, problems may still arise if temperature changes occur and the material has an appreciable coefficient of expansion. There are two effects to be examined here: (1) the dimensional changes that occur between the upper and lower limits of expected temperatures, and (2) the warping of components that may result from non-uniform expansion associated with temperature gradients. Both of these effects must be kept within acceptable limits in designing the processor. The major tools for protecting against dimensional instabilities due to thermal effects include selection of materials and temperature control of the processor environment.

Some of the particular loadings to be expected in the space environment as determined from the literature are given below.

2. Mechanical Loadings

The longitudinal accelerations provided by typical liquid fuel boosters rarely exceed 20.0 g, and the lateral accelerations rarely exceed 1.0 g [4-1]. Nevertheless, specifications for vehicle structures usually require design for higher lateral loadings even when less powerful boosters are used. For example, the environmental design criteria for the Atlas F or the Delta launch vehicles specify -4.0 g longitudinal and $\pm$ 6.0 g lateral design load levels at lift off (positive direction is down). When the vehicle passes through maximum dynamic load conditions, +2.5 g longitudinal and $\pm$ 8.0 g lateral levels are specified. At maximum acceleration, load factors of ± 10.0 g longitudinally and $\pm$ 4.0 g laterally are used [4-2].

Typical shock loadings consist of half-sine, 100 g accelerations of 0.0005 seconds duration, and 100 g ramp accelerations of 0.0001 second duration may be specified [4-2]. A typical random vibration spectrum which a vehicle might experience is shown in Figure 4-1, and the typical acoustic noise level as a function of frequency is shown in Figure 4-2 [4-2].

3. Thermal Loadings

An on-board optical processor will be subjected to thermal effects during launch and after orbit injection. During ascent, thermal energy will be transferred to the outside shroud of the spacecraft via aerodynamic heating. The nose cone stagnation temperature can rise to 1600° F in 100 seconds. The shroud temperature in the payload area can reach 600° F during this time. Depending on the amount of shroud insulation used, on-board equipment may reach temperatures above 200° F in 100 seconds [4-3]. The thermal conditions seen by the equipment mounted inside the satellite depend on the amount of insulation provided in the walls of the satellite, the mounting arrangement of the subject apparatus, and the effect of surrounding equipment.

Heat is also generated by electrical components within the satellite. This heat may be conductively or radiatively coupled to the optical processor. The processor must be isolated, thermally, from surrounding satellite components. This may include insulation to inhibit heat conduction and/or surface coatings with low absorbance to emittance ratios to combat radiative heating of the processor.

C. Design Criteria

1. Dimensional Stability

Optical elements must maintain their shape, spacing, and alignment with each other. Certain dimensional relationships must be extremely stable. This stability requirement demands a structure either insensitive to, or protected from thermal loads. The material must not creep, shrink, or grow with

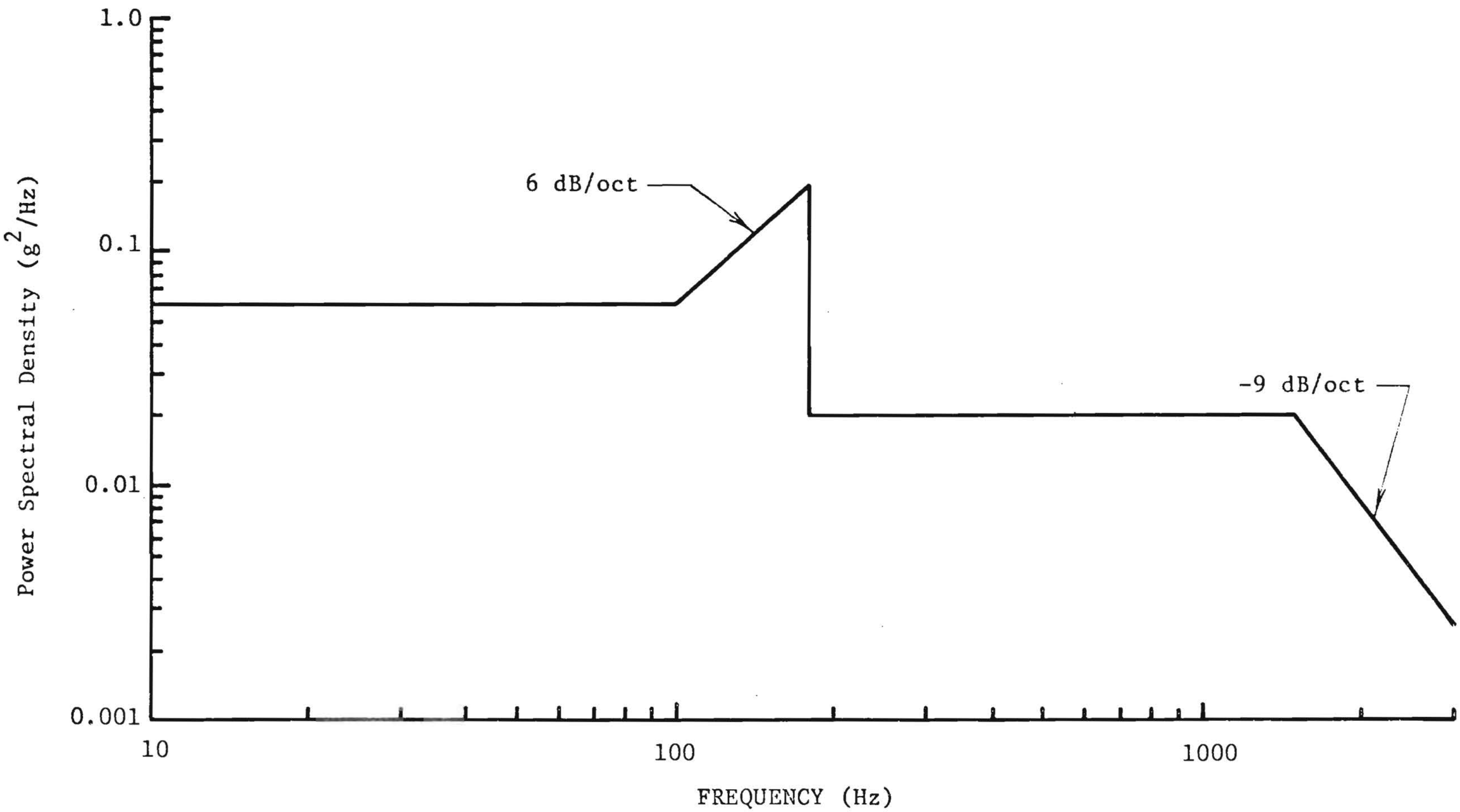

Figure 4-1. Typical Random Vibration Spectrum.
(From Reference 4-2)

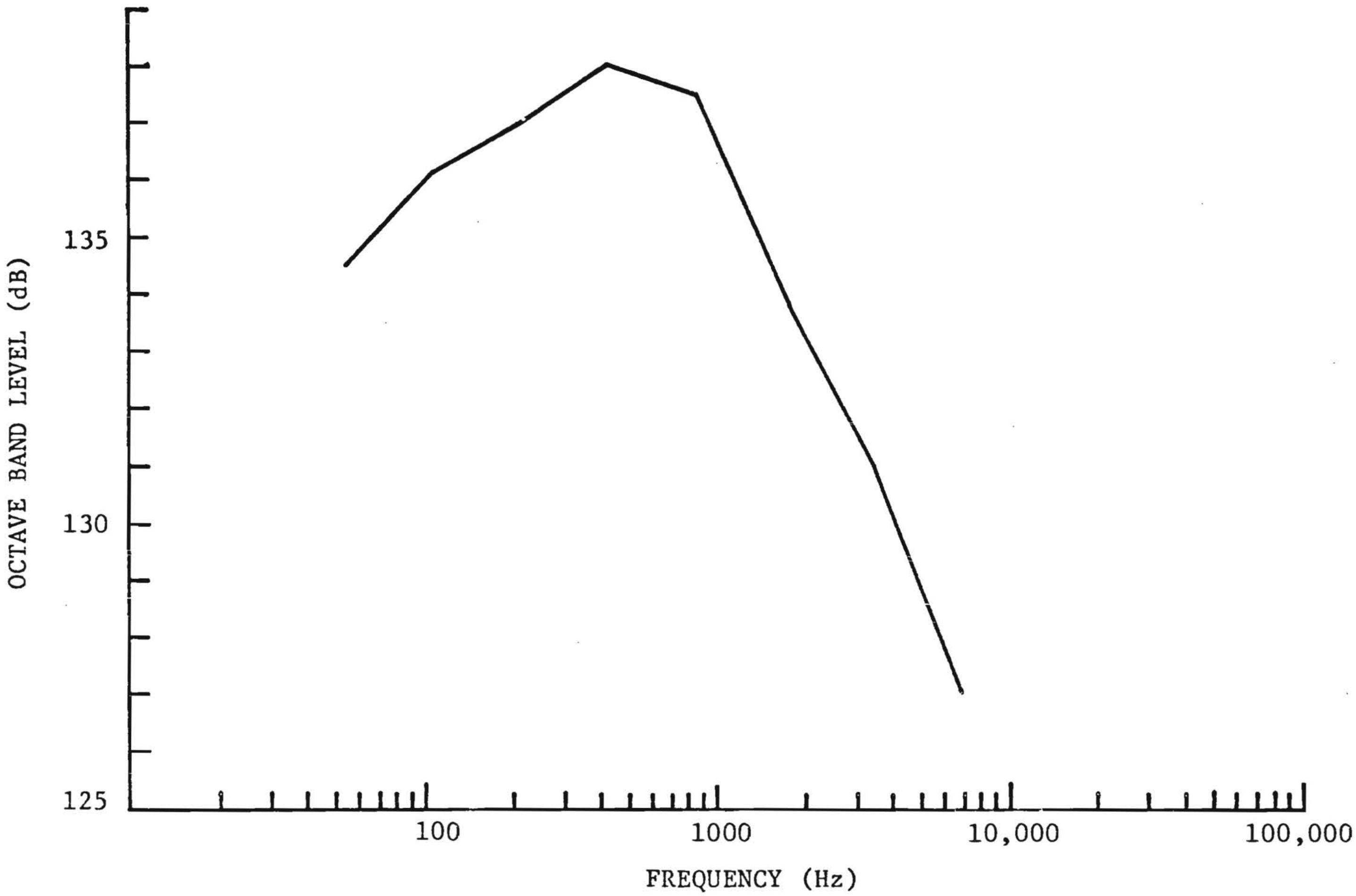

Figure 4-2. Typical Acoustical Noise Level.
(From Reference 4-2)

time.

2. Rigidity

In the construction of optical mechanisms, an important consideration is the rigidity of the structure. Stress is proportional to strain within the elastic limit of the material. Any crystalline material deforms elastically when a load is applied. The maximum allowable deflection can be used to obtain the minimum required rigidity. When the rigidity requirements are known, then the materials of construction can be considered and structural design can begin. The optical processor itself must be stiff enough to achieve two goals: very low deflections in a one g environment, and a high natural frequency. A low frequency mount would then provide isolation from vehicle borne vibration which would otherwise degrade system performance.

3. Strength

Strength as well as rigidity must be examined. Strength is usually specified as tensile strength (resistance to being pulled apart), compressive strength (resistance to loads tending to compact the material), shear strength (resistance to sliding of one section with respect to another). There is also creep strength (resistance to permanent deformation under long exposure to stress), fatigue strength (resistance to repeated reversals of loading), and impact strength (resistance to failure under sudden loads). The ultimate strength normally listed in tables of the properties of materials refers to the stress per unit area at the failure point, whereas the yield-point strength is that stress at which a very small permanent deformation can be detected. The optical processor design must be limited to the yield-point stress as an extreme limit because permanent deformation of the structure would destroy accuracy and alignment. The ratio of stress to strain is called Young's modulus or the modulus of elasticity, E. The direct stiffness, Young's modulus divided by density (E/ρ), is a useful parameter for comparing materials on a stiffness-versus-weight basis. The design for the optical processor structure is directly concerned with this property.

All optical elements, their individual mounts, and the support structure must be strong enough to withstand quasi-static accelerations, shocks, and vibrations imposed during ascent, without sustaining significant permanent deformation.

D. Materials

The ideal material for the structural members of an optical processor would have: (1) low density, to minimize lift-off weight; (2) high thermal conductivity, to minimize thermal gradients; (3) low thermal expansion coefficient, to minimize thermal distortion; (4) high strength to withstand the lift-off loading; and (5) high Young's modulus for rigidity.

The material properties to be considered in the design of a thermal radiation control system for an optical processor are the solar absorbance, α_s, and the infrared emittance, ε. Both α_s and ε vary from 0 to 1.0. The ratio of these two surface properties therefore allows estimation of surface temperatures. The temperature requirements prescribe the values of α_s and ε. Coatings are then chosen to meet these requirements. Table IV-1 lists typical absorbance and emittance values for several finishes and coatings.

The coefficient of thermal expansion, α, is the primary property for use in selecting a material with a high thermal stability. Table IV-2 lists the coefficients of thermal expansion for a number of structural materials. Table IV-3 lists materials selected for their low thermal expansion coefficient. The materials in Table IV-3 are numbered in the right hand column for reference in the discussion which follows.

Invar (Table IV-3, No. 1) is an alloy of iron and nickel containing 36% Ni and less than 1% of other elements. Although it is iron based, it is usually referred to as a nickel alloy. Invar can be obtained which has a linear coefficient of thermal expansion of zero [4-5]. This low value is applicable over a limited range of temperature, however. Hunter [4-5] gives an average value of 0.5×10^{-6} in/in/°F between 32°F and 103°F. Outside this range α reverts to a value close to that of iron and nickel. By replacing some of the nickel with cobalt, an alloy called Super Nilvar (31% Ni) is obtained.

TABLE IV-1

ABSORPTANCE AND EMITTANCE OF SEVERAL FINISHES AND COATINGS

Material	Solar Absorptance α_s	Infrared Emittance ε	α_s/ε
Vacuum-Deposited Aluminum	0.10	0.02	5.0
Aluminized Mylar	0.10	0.02	5.0
Aluminized Kapton	0.47	0.80	0.59
Aluminized Teflon (Type A)	0.17	0.70	0.24
Sandblasted Aluminium	0.42	0.21	2.0
Polished Aluminum	0.31	0.07	4.4
Sandblasted Magnesium	0.63	0.54	1.2
Rokide A	0.15	0.77	0.2
Gray TiO_2 Paint	0.87	0.87	1.0
Z-93 White Paint	0.18	0.95	0.19
S-13G White Paint	0.20	0.90	0.22
Solar Cells	0.80	0.40	2.0
Sauereisen	0.34	0.88	0.4
Fused Silica	0.06	0.84	0.07
Gold Foil	0.20	0.07	3.0
Gold Plating	0.25	0.04	6.2

TABLE IV-2

TYPICAL VALUES OF THE COEFFICIENT OF THERMAL EXPANSION FOR SOLID MATERIALS

Material	Coefficient of Thermal Expansion α (10^{-6} in/in/F°)	
	Low	High
Metals:	0.0	21.8
Irons and alloy irons	4.5	10.5
Steels	5.2	10.6
Aluminum alloys	9.0	13.4
Cobalt alloys	6.8	9.9
Copper alloys	9.0	12.0
Lead alloys	14.4	16.3
Magnesium alloys	14.0	21.8
Nickel alloys	0	13.2
Tin alloys	13.0	----
Titanium alloys	4.5	6.0
Zinc alloys	6.0	19.3
Zirconium alloys	3.1	3.6
All other metals	2.5	10.9
Plastics:	1.7	167.0
Acetals, Alkyds and thermosat carbonate	10.0	60.0
Acrylics and Styrenes	0.46	6.0
Alloys	35.0	121
Cellulose acetates	44.0	167
Epoxies	1.7	50.0
Fluorocarbons	17.0	140
Foams, rigid	5.0	97.0
Melamines	8.2	27.8
Nylons	12.0	55.0
Phenol-formaldehyde	17	44
Phenolics	8.3	25.0
Poly-(ester, ethylene, carbonate, etc.)	3.0	167
Silicones	25.0	50.0
Composites:		
Advanced composites	1.3	7.9
Laminated thermosetting materials	5.0	11.0
Vulcanized fibre	1.0	2.0
Ceramics:	0.2	27.0
Mechanical and electrical ceramics	0.2	4.0
Refractor ceramics	0.28	7.78
Carbides	1.73	5.80
Glasses	0.00	5.78
Carbon, graphite	0.40	9.4
Mica products	5.2	27.0

TABLE IV-3

TYPICAL PROPERTIES OF LOW THERMAL EXPANSION MATERIALS

Material:	Thermal Expansion Coefficient in/in/F°	Specific Gravity	Thermal Conductivity BTU/hr/ft²/F°/ft	Specific Heat BTU/lb/F°	Tensile Modulus 10^6 psi	Tensile Ultimate 10^3 psi	No.
Metals:							
Invar	0-1.5	8.0	7.8	0.123	21.4	65-90	1
Mo-0.5Ti, 0.1 Zr	2.7	10.2	84.5	0.065	46	125	2
Tungsten	2.5	19.4	96.6	0.034	59	220	3
Plastics:							
Epoxy Novolacs	1.7-2.2	1.7	-----	-----	--------	5.2-5.3	4
High Performance Resins	1.6-3.0	1.22	-----	-----	0.48-0.5	9.6-12.0	5
Composites:							
Boron/Eposy ∥ to fiber	1.3	2.0	-----	0.278	30	180-190	6
⊥ to fiber	7.9	---	-----	-----	2.7-2.8	10.0	
Graphite/Eposy ∥ to fiber	-------	1.6	-----	-----	22.5-25	110-212	7
⊥ to fiber	-------	----	-----	-----	1.3	8.0	
Vulcanized Fiber ∥ to fiber	1.2	0.9-1.3	0.17	0.403	1.2-0.8	6-14	8
⊥ to fiber	-------	----	-----	-----	0.8	--------	
Ceramics:							
Alumina	2.1-4.3	3.4-3.9	10.7-21.3	0.330	30-50	20-40	9
Alumina-Chromite	2.6	----	31	0.230	--------	--------	10
Boron Carbide	1.7-3.0	2.4	16	0.25-0.53	42-65	45	11
Borosilicate Glass	1.7	2.2	0.68	0.17	9.3-10.5	--------	12
Carbon & Graphite	0.6-9.4	1.2-2.2	3-215	0.16	4.0	14.0	13
Corderite	2.0-2.1	2.0-2.7	1.0-2.4	-----	7	3	14
Lithia Porcelain	0.6	2.3	-----	-----	--------	--------	15
Mullite	0.6-3.0	3.0-3.3	1.4-16	0.230	--------	14-18	16
Nb_2O_5	0-1.0	4.5	-----	0.12-0.16	4	--------	17
Polycrystalline Glass	0.0-1.1	2.5	0.97-1.13	0.19-0.20	12.0-13.4	--------	18
Silica Glass	0.3-0.4	2.2	0.85	0.170	9.6-10.0	--------	19
Silicon Carbide	2.2-3.0	2.5-3.2	9-25	0.15-0.34	13-70	3-20	20
Standard Electrical	2.0-2.7	2.4-2.5	0.9-1.6	-----	10	7.0	21
Tungsten Carbide	2.5-4.5	13-15.2	26-50	0.05-0.08	100	130	22
Zircon	1.3-2.5	3.6-3.7	2.9-3.6	-----	21-24	12	23

This alloy is essentially identical to Invar. An alloy containing 32% nickel, called Elinvar, not only has a low α but also has a constant modulus of elasticity over the range of 0 to 100° F. Invar can be obtained in the form of bar, plate sheet, strip, wire, tubing, forgings, and castings. It can be welded by conventional acetylene torch, metal arc, carbon arc, and resistance methods.

The molybenum alloys are available in most forms. They are weldable by TIG and resistance methods. The alloy listed (Table IV-3, No. 22) is used for high temperature and space vehicle structures. Tungsten (No. 3) is difficult to machine, but can be handled with carbide tools. It is weldable and is available in most forms. Osmium has a low α, but since it is not workable it is available only as cast parts.

The plastics, in general, have very high expansion coefficients. The epoxies listed (Nos. 4 and 5) are exceptions because they were developed for high temperature applications. They are also more resistant to acids and weather than other epoxy systems.

The boron/epoxy and graphite/epoxy composites (Nos. 6 and 7) are extremely high strength materials. They are also very light weight, but they have directionality properties which may create problems. The properties have been overcome by using a four layer laminate with each layer at 45° to the preceding layer, but the thermal properties for such a laminate are not known.

Vulcanized fibre (No. 8) is commonly used as an insulating material, and also to make gears, cams, bushings, grommets, switch handles, terminal blocks, and armature slot wedges.

The ceramics, overall, have the lowest coefficient of thermal expansion. The materials listed in Table IV-3 were gathered from references 4-6, 4-7, and 4-8. The carbides (Nos. 11, 20 and 22) are not available in sizes large enough to be applicable for the processor. Borosilicate glass (No. 12) is the familiar heat resistant laboratory glass. A recrystallized form of graphite (No. 13) is used in the manufacture of rocket nozzles and nose cones.

The polycrystalline glasses listed (No. 18) are Dow Cornings's 9608 Pyroceramics and Owens-Illinois CerVit. Pyroceram is used to make Corning Ware cooking utensils and also telescope mirror blanks. Owens-Illinois' Cervit glass-ceramic has a zero coefficient of thermal expansion. Cervit is used for telescope mirror blanks as large as 3 meters in diameter for orbiting telescope systems. Nb_2O_5 (No. 17), a ceramic, has an expansion coefficient of zero, but its other properties are not presently known.

If portions of the optical processor are to be exposed to the vacuum conditions of free space the choice of material must be made with the outgassing of materials a consideration. Materials acceptable for free space operation are specified in Reference 4-9.

E. Example Design

For purposes of illustrating some of the important aspects of the mechanical design of a processor, these principles have been applied to an assumed design. This example processor is shown in Figure 4-3. Specific dimensions have been associated with the design so that the various design calculations can be carried out.

Each optical element is individually mounted on an L-section beam, which is to be fabricated of Invar (36% Ni, Fe). The beam's mounting surfaces are ground flat. Element mounts can be pinned in place, or more precise methods can be used if required. Note that the element mounts have been omitted from the figure.

The L-section beam is simply supported at each end by a soft, vibration isolation pad. It may be necessary or desirable to enclose the processor in a lightweight can.

No thermal control has been attempted. The main structure of Invar should control thermally induced distortions.

1. Mass Estimate

The L-beam has legs of 11.43 centimeters (4.50 inches) and 12.38 centimeters (4.87 inches), 0.95 centimeters (0.37 inch) thick and 86.36 centimeters (34.00 inches) long. The beam is to be fabricated of Invar, which has a density of 8.0 grams per cubic centimeter (0.29 pounds per cubic inch). The beam has a mass of 15.4 kilograms (34 pounds). The optical

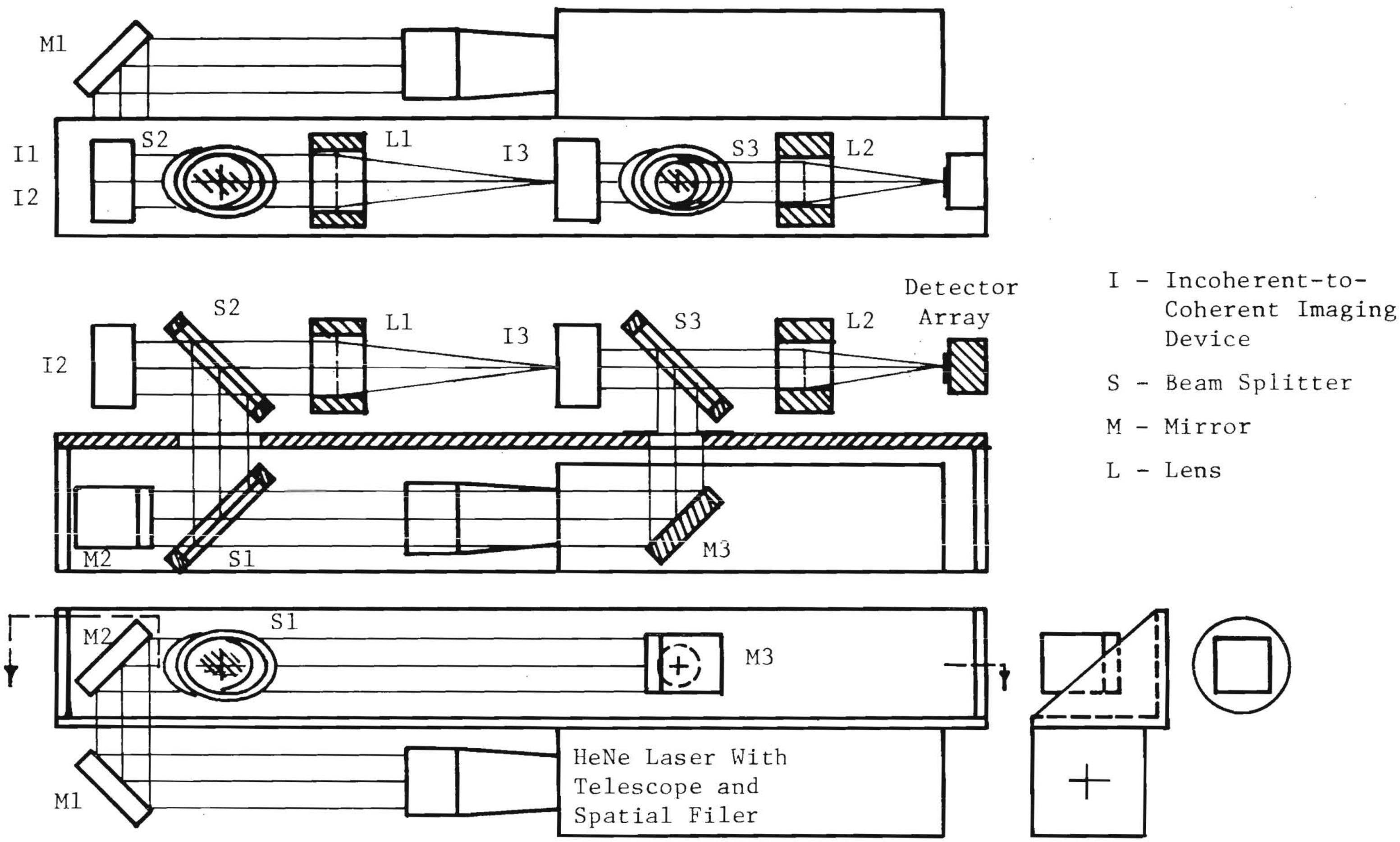

Figure 4-3. Arrangement of Optical Elements and Support Structure.

elements, mounts and laser add an estimated 9.5 kilograms (21 pounds). The estimated total mass is 24.9 kilograms (55 pounds).

2. External Dimensions

The processor design as depicted in Figure 4-3 will fit within a 24.1 x 21.6 x 86.4 centimeter (9.5 x 8.5 x 34.0 inch) rectangular volume.

3. Beam Stiffness, Deflection, and Natural Frequency

The moment of inertia, I, is found by utilizing the parallel-axis theorem, expressions for the product of inertia, axis rotation relations, and equations for moments of fundamental shapes. The moment of inertia of the beam section was computed about two orthogonal axes passing through the section centroid, parallel to the legs of the "L." The moments are 269 and 328 centimeters^4 (6.46 and 7.89 inches^4). To simplify further calculations, problems of location of shear center relative to load and principal moments of inertia were neglected, and the beam was assumed to be symmetrical, with a moment of 269 centimeter^4 (6.46 inches^4), and a mass of 24.9 kilograms (55 pounds).

If the beam is simply supported at the ends, its own mass (at 1 g) will cause a central sag of 0.0005 centimeters (0.0002 inches). If the beam is supported symmetrically at two points 47.83 centimeters (18.83 inches) apart, deflections are minimized at 0.000011 centimeters (0.0000044 inches). If the beam were supported in this manner during optical alignment, alignment would be virtually unaffected by the weightless operational environment.

The soft vibration isolation mounts would have little effect on the vibration of the beam at its own natural frequencies. The first mode would be "free-free" flexing. This occurs at the following frequency [4-4]

$$\begin{aligned} \omega &= 22.4\sqrt{\frac{EI}{\mu \ell^4}} \\ &= 3512 \text{ radian/second} \qquad (4\text{-}1) \\ &= 559 \text{ Hz} \end{aligned}$$

where ω = fundamental frequency

ℓ = length of member

E = Young's Modulus

I = moment of inertia

μ = mass per unit length

The frequencies of the higher modes are related to the frequency of the fundamental mode as follows:

$$\omega_2 = 4\,\omega$$

$$\omega_3 = 9\,\omega$$

$$\omega_4 = 16\,\omega$$

To isolate the beam from frequencies high enough to excite it, soft vibration mounts are used. If these yield a mounted frequency one-fifth as large as the beam natural frequency, transmissibility in the critical frequency range will be low. A mount frequency of 100 Hz requires a mount spring rate of 98,110 Newtons per centimeter (56,000 pounds per inch). This is much stiffer than conventional vibration mounts, which implies that vibration isolation may be obtained with conventional mounting arrangements.

4. Strength

Let us assume the 85 centimeter long optical processor to be oriented at launch such that the lift-off acceleration load acts along the axis of the base member. The stress, σ, on the member is defined as the load, P, divided by the cross-sectional area, A. For acceleration loads, P = ma, where m is the mass and a is the acceleration. Therefore

$$\sigma = ma/A \tag{4-2}$$

which expresses the stress level in an axially loaded member. This stress must be considered to be the minimum tensile yield strength, σ_y, because permanent deformation of the structure is not acceptable. Solving for the acceleration yields

$$a = \sigma_y A/m \qquad (4-3)$$

Substituting the yield strength of Invar, 27,600 Newtons per square centimeter (40,000 psi), the estimated mass of the processor, 24.9 kilograms, (55 pounds) and the cross-sectional area of the L-beam, 21.8 square centimeters (3.4 square inches) yields a maximum allowable acceleration load over 2400 g's.

The ability of the beam to resist lateral loads without plastic deformation is critical. The section modulus is $z = I/c = 269/8.33 = 32.3$ centimeters^3 (1.97 in.^{3}). Invar has a minimum elastic limit $\sigma_y = 27{,}600$ Newtons per square centimeters (40,000 psi). The maximum permissible bending moment is $M = \sigma_y z = 27{,}600 \times 32.3 = 8890$ Newton-meters (78,800 inch pounds). When the beam is simply supported at its ends, a 1 g lateral acceleration produces a maximum bending moment of 27 Newton-meters (234 inch-pounds). The ratio of the maximum permissible moment to the moment corresponding to 1 g is the maximum permissible lateral acceleration, 330 g.

5. Dynamic Loading

The quasi-static acceleration design load expected is 30 g, well below the 330 g limit.

The most severe shock is the 100 g (981 m/sec^2) half-sine of 0.0005 second duration. The duration is quite short compared to the natural period of the mounted optical processor, 0.002 seconds. Therefore the shock will appear (from the processor's viewpoint) as a velocity step of magnitude

$$v = \int a\,dt \qquad (4-4)$$

$$= \int_0^{0.0005} (981) \sin 2000\pi t\,dt$$

$$v = 31.2 \text{ centimeters/second (12.30 inches/second).}$$

The equation for the displacement of the vehicle, from the moment of the shock, is

$$X_v = vt. \tag{4-5}$$

The equation for the displacement of the processor, from the moment of the shock, is

$$X_p = - \frac{v}{\sqrt{k/m}} \sin (\sqrt{k/m}t + vt). \tag{4-6}$$

The maximum acceleration of the processor is

$$\ddot{X}_{pmax} = v\sqrt{k/m} \tag{4-7}$$

$$= 196 \text{ meters/sec}^2 \text{ (7728 in./sec.}^2\text{)}$$

$$= 20 \text{ g.}$$

In the above equation m is the processor mass and k the mount stiffness. Note that neither quasi-static or shock loading produces accelerations larger than 10% of the permissible 330 g.

6. Dimensional Stability

The L-beam is fabricated of Invar, which has a coefficient of thermal expansion near zero. Therefore, temperature gradients induced by external or internal heating should produce no distortion.

7. Thermal Considerations

The processor is assumed to be located in a temperature controlled environment of unknown stability. Internal heat generation (5 watts consumed by the laser, producing a 5 milliwatt beam) insures the existence of temperature differentials.

Thermal expansion is related to temperature change by the equation

$$\delta = \alpha L \Delta T, \tag{4-8}$$

where δ = thermal expansion (inches)

α = coefficient of thermal expansion (inch/inch/F°)

L = original length

ΔT = temperature change.

The processor elements should be aligned to within 100 μm (0.0004 in.) over the ∿ 70 cm. (28 in.) spacing of the components. Assuming that the apparatus will see a maximum temperature change of 11°C (20°F) in an insulated satellite the maximum allowable value for the coefficient of thermal expansion, α, of the material is calculated as

$$\alpha = \frac{\delta}{L\Delta T} = \frac{0.0004 \text{ in.}}{28 \text{ in. } (20°\text{F})} = 0.7 \times 10^{-6} \frac{1}{\text{F}°} \tag{4-9}$$

Since α for most structural materials is of the order of 10×10^{-6}/F°, it is obvious that the structural material must be carefully selected. The choice of Invar provides a material that can meet the thermal requirement.

V. ELECTRONICS

A. Information Source Characteristics

The source of a large portion of the input for an on-board optical processor would be picture formatted data from television cameras or multispectral scanners. Television data would be formatted such that there were a specific number of frames per second each consisting of a number of scan lines depending on the system resolution. The scan lines would probably have an interlace pattern if the pictures were intended for real time viewing and if flicker presents a problem. The standard American monochrome television system uses a frame rate of 30 complete pictures per second consisting of 60 fields interlaced in a ratio of 2:1. Each frame consists of 525 scan lines of which at least 483 are active picture lines. The lines not actually used for picture information are used for vertical synchronization purposes. Of each horizontal scan line which is of 63.5 microsecond duration, 82 percent, or 52.1 microseconds, is used for actual picture information while 18 percent is used for horizontal synchronization information. The standard television system has a resolution of 350 to 400 lines vertically with the horizontal resolution depending on the video bandwidth available. A bandwidth of 4.25 MHz makes possible a horizontal resolution of about 345 lines [5-1]. These television standards have been widely used for space purposes in the past and have the advantage of compatibility with a wide variety of existing equipment. Special television formats may be desirable where higher resolution or specific scene information may dictate. Such nonstandard systems involve the expense of special system hardware.

Multispectral scanners (MSS) used on many spacecraft in recent years [5-2] and proposed for use on future spacecraft [5-3], gather data by imaging the surface of the earth in several spectral bands simultaneously through the same optical system. The Earth Resources Technology Satellite (ERTS) uses a four band MSS in the 0.5 to 1.1 micrometers wavelength region. From nominal orbital altitude (915 kilometers) the instantaneous field of view of the sensors is 79 meters. Six optical fibers are used in the detection device in each of the four spectral bands. These fibers are arranged in a 4 x 6 matrix in the focused area of a telescope. Light in each fiber is conducted to an individual detector through an optical filter. A line across the satellite track is scanned by an oscillating mirror in the MSS. An image of a line across the satellite track is swept across the fibers each time the mirror scans, causing a video signal at the output of the detectors to be produced for each of six adjacent scan lines in each of the four spectral bands. The signals are sampled, digitized, and formatted into serial data by a multiplexer. The sampling interval is 9.95 microseconds which corresponds to a cross track motion of the instantaneous field of view of 56 meters.

The along-track scan is produced by the orbital motion of the spacecraft. The nominal orbital velocity causes an along-track motion of the subsatellite point of 6.47 km/sec. By selecting the rate of oscillation of the mirror, the subsatellite point moves 474 meters along-track during each active scan and retrace cycle. The width of the along-track field-of-view of the six detectors in the four spectral bands is also 474 meters. The width of the scan normal to the track motion is 185 km. The scan timing is such that the output of the first detector in a spectral band lies adjacent to the output of the sixth detector in the same frequency band produced by the previous scan. Thus, across-track lines are scanned six at a time. To produce a square picture representing 185 km (100 nmi) across-track and 185 km along-track would require 28.5 seconds.

The proposed Earth Observatory Satellite is to have a 5-band MSS with a resolution of 80 meters and a 6-band thematic mapper with a resolution of 30 to 40 meters.

B. Electronic Characteristics of Real Time Optical Input Devices

One of the primary functions to be performed by the electronic system of the optical data processor is to interface the signal source, whether it be a television formatted signal or a signal produced by a multispectral scanner, with the input device of the optical processor. From the discussion in Section III concerning the various input devices two of these devices appear to be reasonable candidates as "real time" input devices to a future optical processor. These devices are the ITEK PROM and the Hughes Liquid Crystal Modulator.

Two other candidate devices, the GE Coherent Light Valve (CLV) and the

Image Forming Light Modulator (IFLM), are considered to have serious limitations for on-board spacecraft applications. The CLV, while providing very good coherent imagery suffers from short lifetime (when considered in terms of spacecraft equipment), considerable peripheral equipment complexity, and the present uncertainties of a zero g environment for the "oil" film used in the device. The IFLM also suffers from lifetime and equipment complexity considerations resulting from its high intensity electron beam and crystal cooling requirements.

Some characteristics of these devices which impact the electronic system will be considered. The PROM exhibits high resolution, good contrast, high sensitivity, rapid response time, storage capability, and contrast reversal capabilities. Equipment complexity of the PROM is fairly extensive. Power supply requirements involve a 2 kilovolt high voltage power supply and the switching circuitry involved in reversing this high voltage supply across the PROM. Writing is accomplished with blue light at a wavelength of about 400 nm, and reading is accomplished with red light at a wavelength of 633 nm. Erasure of the image is accomplished with high intensity white light supplied by a Xenon flash tube. The maximum contrast is about 10000:1, and published data indicates no known limit or lifetime; however, the isolation between the input and output images is less than 1000:1. The optical aperture is 25 x 25 mm. Recycle rates of 30 Hz have been demonstrated [5-4].

The energy required to write on the PROM is a function of the write time. For write times in the range of 10^{-8} to 10^{-5} seconds the write energy is between 10^3 and 10^4 ergs/cm^2. For write times in the range of 10^{-4} to 10^{-1} seconds the write energy is approximately 100 ergs/cm^2. Variation of the voltage across the PROM can produce various image processing functions. Among these are: (1) edge enhancement, (2) contrast reversal (3) level slicing and (4) reduction of the dc spot produced in the transform plane.

The Hughes Liquid Crystal Modulator requires a very simple ac power supply which furnishes approximately 5 V rms at 5 mA in the frequency range of 10 to 20 kHz. The contrast ratio is presently slightly less than 100:1 with values greater than 100:1 expected as development continues. Write time is a function of light intensity and can approach a large fraction of a second for low light intensities. Published values indicate that with an input light intensity of 10 μwatts/cm^2 the excitation time is 240 μsec. Decay time of the liquid crystal devices is defined as the time for the response to fall from maximum effect to 10 percent of the maximum value after the excitation is removed. Times quoted range from 10 to 30 milliseconds. The liquid crystal devices which are based on thin film technology, have the potential of low costs in production quantities. Write power requirements range from 3.3 μwatts/cm^2 at threshold to approximately 1000 μwatts/cm^2 at saturation. Contrast reversal and other image processing techniques may be produced by variation of the ac power supply voltage or frequency.

C. Electronic to Optical Conversion Devices

Since the signals to be processed will most likely be in the form of electrical time waveforms produced by television or MSS devices, and the input signals required by the incoherent to coherent real time optical input devices are incoherent light, a conversion device must be provided. Candidates for such conversion devices are cathode ray tubes, storage tubes, and amplitude modulated laser beams. Each of these devices is represented by a range of operating parameters which unfortunately do not necessarily match the optical input device requirements.

Cathode ray tubes are available in several shapes and sizes. Various phosphors are available which provide different spectral distribution of light energy, and have widely different persistence characteristics.

Common direct view cathode ray tubes provide a light output in the range of 30 to 150 foot-lamberts, while projection cathode ray tubes can provide up to 20,000 foot-lamberts of light output, but require anode voltages in the range of 25 to 80 kilovolts. Because of breakdown problems, it is desirable to avoid such power supply voltages in a space environment. The phosphors used in projection tubes may also display aging, and are subject to damage if the sweep rates are not maintained. CRT's for airborne applications are available with light output up to 12000 foot-lamberts, although the resolution of these tubes is generally low.

Cathode ray tube phosphors have a wide range of persistence characteristics, ranging from very short to very long. Very short phosphor persistence is in the range of tenths of microseconds to decay to 10 percent of maximum brightness. For example, the phosphor designated P-16, which has a bluish-purple color, has a very short persistence. Phosphors having a very long persistence are those designated P-33 and P-34 with approximately 2 and 100 second decay time respectively. Phosphors are available that have persistence values between these extremes. The common P-4 phosphor used for monochrome television service is white in color and has a persistence of 60 microseconds.

Resolution of cathode ray tubes is dependent on the electron beam spot size at the phosphor and the grain of the phosphor. High quality cathode ray tubes have a resolution of the order of one thousandth of an inch (2.54×10^{-3} cm).

Direct view storage tubes provide the capability of writing an image on a storage surface and displaying the image for viewing over a long period of time. Light output of these tubes ranges from 20 to 2500 foot-lamberts. Storage times are in the range of tens of seconds to hundreds of seconds. Some special purpose tubes have even longer storage times. Erase times range from the order of a millisecond to a second. Resolution of up to 150 lines per inch (59 lines per cm) is available with a usable screen diameter of 4 inches (10.2 cm).

Lasers provide another source of light energy which could be used to write an image on an optical input device. Writing on the PROM has been accomplished by projection using a HeCd laser through an optical transparency. For real time laser image formation, a small diameter laser beam could be scanned in a raster pattern with its amplitude modulated by the electrical signal representing the image. Modulators are available having bandwidths of several megahertz. Scanning of the laser at television rates presents problems, however, particularly for the horizontal rates involving large deflection angles. Scanning at the horizontal rate would involve complex acoustical-optical apparatus of a size and complexity questionable for spacecraft use [5-5]. Slower rates may be accomplished using electro-mechanical means.

D. General Electronic System Considerations

Writing on either the Liquid Crystal Modulator or the PROM presents problems unique to each of these devices. Some of the problems of operation of each of these devices from the electronic viewpoint will be discussed separately.

It would be desirable to operate the Liquid Crystal Modulator at the television rate of one complete picture every 33 milliseconds. One complete image would then be processed by the optical system, and the Liquid Crystal Modulator erased and prepared for the next image. Since the Liquid Crystal Modulator has no erase capabilities, the image would be eliminated by letting it decay to a value sufficient to write over the previous image with a new one. Decay times specified are 15 to 30 milliseconds which represent one-half to almost a complete television frame time. Thus operation at television rates would not be possible in a system requiring that the complete image be present at a given instant of time for parallel optical processing. Every other frame operation appears possible from the viewpoint of the liquid crystal decay characteristics.

The decay of the crystal presents still another problem from the viewpoint of establishing a complete image, since for sequentially developed images, the first written portion of an image decays before the last portion can be written. One convenient converter format is to write the picture on the electro-optic medium electronically by imaging the light produced by a CRT or similar device in a raster scan mode from a time waveform representing the image video data. The time span for producing a complete image is approximately 33 milliseconds. Measurements of the decay rate of the liquid crystal modulator indicate that the first few lines of the image will have decayed to less than 10 percent of their initial intensity by the time the end of the image is written. This problem was investigated on a first look basis in the digital simulation carried out in this investigation, and discussed in Section VI.

Another problem with the liquid crystal input devices is that of excitation time. Excitation times for the crystal are stated to range from 250 milliseconds for light levels of 10 μwatts/cm^2 to less than 5 milliseconds for saturation light levels (approximately 1000 μwatts/cm^2). The dependence of excitation time on intensity would present a real problem in forming an image which would use the full available gray scale of the liquid crystal modulator. Excitation times of 0.25 second would limit the rate at which TV resolution images may be written on the crystal to 4 per second or less. A related problem is that in a single TV image, each picture cell is addressed for a time interval which is less than 1 microsecond, and since the liquid crystal modulator cannot store and integrate the light intensity, no picture would be formed on an image created in this manner.

These operating characteristics indicate the need for an electronic storage device on which the image may be written at television rates and the complete image displayed to the liquid crystal for a much longer time than the television frame time.

Direct view storage tubes are devices which can provide this function. The characteristics of these tubes are, however, not ideal for the requirements demanded by the electronic to light conversion devices for the input to an optical processor. First the resolution obtainable from commercially available storage tubes is not what is desirable for the conversion device at the input to the optical processor. A survey of device specifications indicates that a maximum resolution of 150 lines/inch is obtainable in a storage tube with a usable face diameter of 4 inches [5-6, 5-7]. When reduced to the television format with an aspect ratio of 4:3, the maximum usable width is 3.2 inches and the height is 2.4 inches. This would result in a horizontal resolution of 480 lines and a vertical resolution of 360 lines. This compares favorably with standard monochrome television resolution but is far short of the resolution required for processing of multispectral images.

Erase time for the storage tubes appears to be no problem since some storage tubes may be erased in several milliseconds and are intended for operation at television rates.

For applications where a CRT or storage tube larger than the modulator aperture is employed because of resolution requirements, image demagnification by a lens system will be necessary. The geometry of the imaging system will depend primarily on the intensity required by the modulator and the MTF which can be tolerated. A simple geometrical optics analysis reveals the important considerations for imaging a CRT onto a smaller aperture.

The light intensity, I, incident on the coherent optical input device is related to the effective brightness, B', of the CRT by the expression

$$I \approx \frac{2\pi B' d_1^{\,2}}{d_3^2} \left(1 - \frac{2S_i}{\sqrt{4S_1^{\,2} + d_2^2}}\right), \tag{5-1}$$

where d_1 is the diameter of the CRT,

d_2 is the diameter of the imaging lens,

d_3 is the diameter of the modulator image,

$S_1 = f \dfrac{(d_1 + d_3)}{d_3}$ is the CRT to lens spacing, and

f is the focal length of the lens

The effective brightness, B', is a function of the spectral response of both the CRT phosphor and the coherent input device. The effective luminus flux of the CRT can be written an

$$F' = 680\ P_o \int V(\lambda)R(\lambda)S(\lambda)d\lambda, \tag{5-2}$$

where F' is the effective luminus flux in Lumens,

$P_o R(\lambda)$ is the spectral power function of the CRT,

$V(\lambda)$ is the visual response function, and

$S(\lambda)$ is the spectral response function of the coherent input device.

If the functions $R(\lambda)$ and $S(\lambda)$ are relatively narrow, the effective luminus flux in a bandwidth $\Delta\lambda$ centered at a given wavelength λ' can be written

$$F' = 680\ P_o \Delta\lambda\ V(\lambda')S(\lambda') \tag{5-3}$$

For example, if the spectral response of the CRT phosphor and the coherent input device both peak at about $\lambda' = 5550\mathring{A}$, $V(\lambda') = 1$ and

$$B' = 5.04^{-7} B \text{ watts/SR cm}^2, \tag{5-4}$$

where B is the brightness expressed in foot-lamberts.

This illustrates the design procedure for determining an appropriate imaging system; we will assume the foregoing spectral response characteristics and examine the relation

$$H = 5.04 \times 10^{-7} TB \text{ watts/cm}^2, \tag{5-5}$$

$$\text{where } T = \frac{2\pi\, d_1^2}{d_3^2} \left(1 - \frac{2S_1}{\sqrt{4S_1^2 + d_2^2}}\right), \text{ and} \tag{5-6}$$

H is the image irradiance at the coherent input device.

The function, T, can be made independent of lens diameter by substituting the f number of the lens which is defined as

$$f = \frac{f}{d_2} \tag{5-7}$$

into the relation

$$S_1 = \frac{f(d_1 + d_3)}{d_3} = f \frac{d_2}{d_3} (d_1 + d_3), \tag{5-8}$$

and substituting this relation into T. Performing these substitutions yields the following approximation for the intensity of the image at the coherent input device:

$$H \approx 3.17 \times 10^{-6} \frac{d_1^2}{d_3^2} \left(1 - \frac{10 f}{\sqrt{1 + 100 f^2}} \right) B \qquad (5\text{-}9)$$

The foregoing approximation should only be employed for $d_2 > d_1$ if a reasonably high degree of accuracy is required. Figure 5-1 shows the variation of T as a function of f number for an imaging system with $d_1 = 4$ inches and $d_3 = 1$ inch corresponding to a demagnification of 4:1, and indicates that a fast imaging lens is required for low light loss. In Figure 5-2, the irradiance, H, in the image plane has been calculated as a function of the CRT brightness for several different speeds of the imaging lens. The range of irradiance corresponding to typical CRT brightness parameters is shown. It can be seen that imaging with a demagnification of 4:1 would require a CRT brightness of about 400 foot-lamberts for an image intensity of 100 $\mu W/cm^2$ (saturation level for the Liquid Crystal Modulator).

Electronic considerations of the PROM are different in some respects than those of the Liquid Crystal Modulator. The Liquid Crystal Modulator has no integration capability and displays a threshold excitation level which must be exceeded by the writing source before a response is obtained. The PROM has integration capabilities which make possible the buildup of an image by a series of exposures each of which may be below the required exposure energy. The PROM has a fast response to excitation energy which makes possible the writing of a television image on the PROM at the scan rates of standard television signals. Its exposure characteristics are specified as energy applied to the crystal per unit area. To use the full dynamic range of the device exposure energies of 10^4 ergs/cm^2 are required, which result in a contrast ratio of approximately 10^4. Writing on the PROM is accomplished by using blue light and reading is performed by the use of red light. The PROM is less sensitive to red light than to blue light by a factor of approximately 400, and once an image is written on the device it can be stored for about 1 hour with no appreciable image degradation.

Writing techniques usable for the PROM differ considerably from those used for the Liquid Crystal Modulator. The response of the PROM is fast (useful

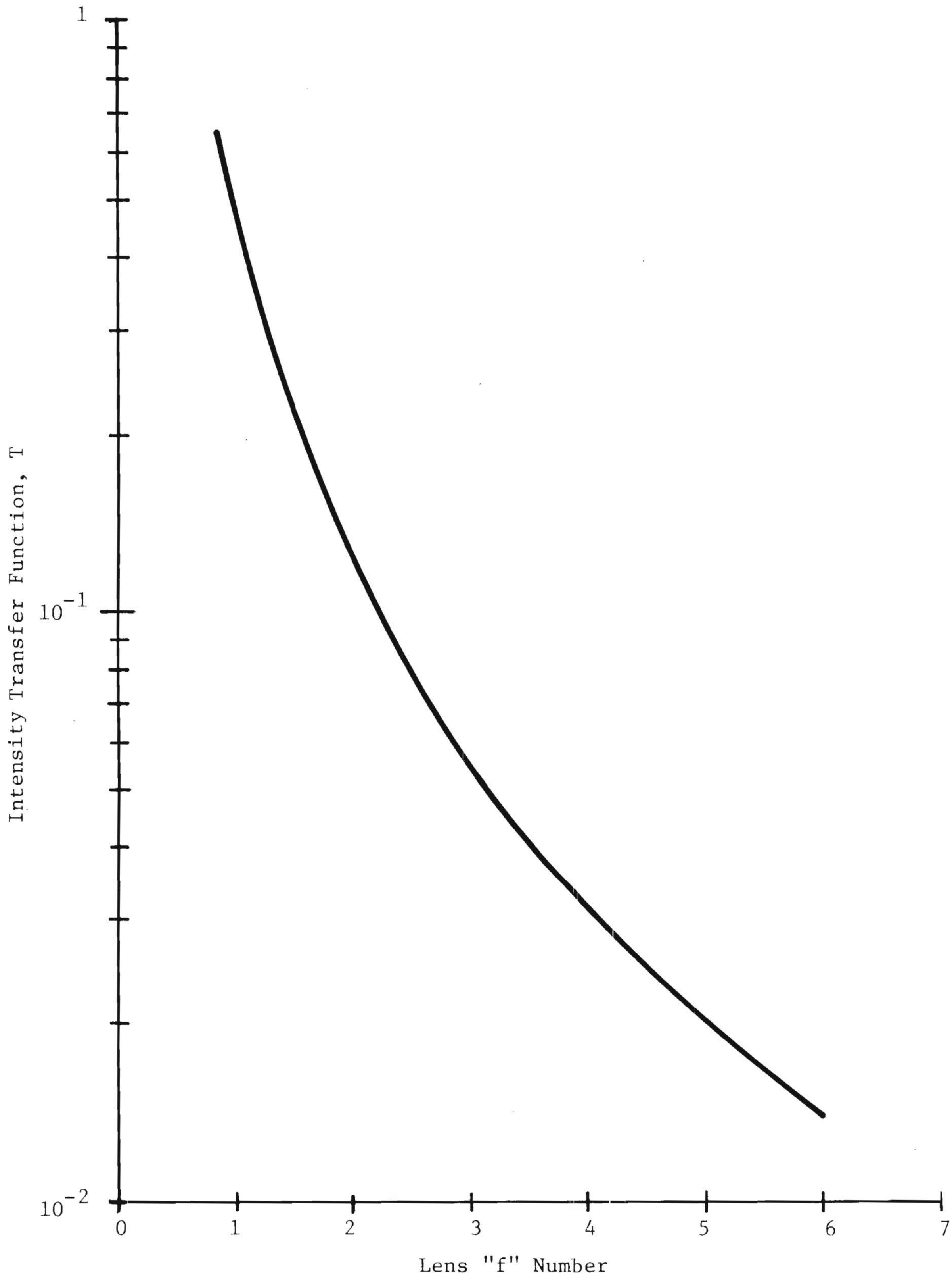

Figure 5-1. Intensity Transfer Function of an Imaging Lens with a Demagnification of 4:1 as a Function of "f" Number.

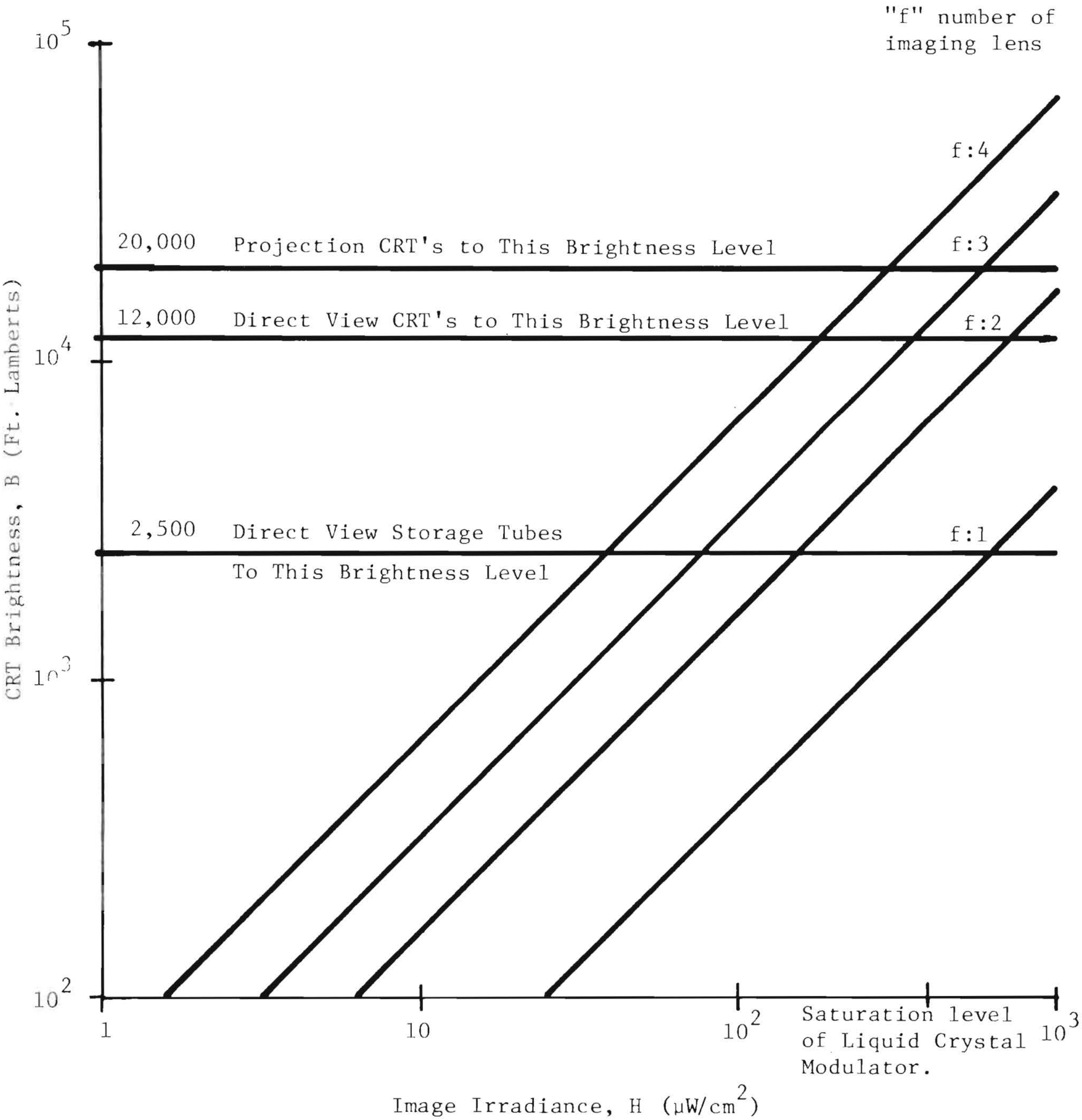

Figure 5-2. Irradiance of a CRT Image With Demagnification of 4:1 for a Spectral Response of the CRT Phosphor Peaked at λ = 0.555 μm.

response it obtained at 10 nanoseconds) and television images may be written during a single frame time. Writing in this manner could be accomplished by using a scanning laser. Comparison of the PROM and the Liquid Crystal Modulator will be made at a contrast ratio of 100:1, which is near the maximum value obtainable with the Liquid Crystal. It must be realized that this contrast ratio is two orders of magnitude less than the maximum obtainable with the PROM and is used here for comparison purposes.

The energy required by the PROM to obtain a contrast ratio of 100:1 is approximately 550 ergs/cm^2 at a wavelength of 440 nm. For a commercial television format the image aspect ratio is 4:3 which in a one inch square PROM (2.54 cm square) would give a usable area of 2.54 x 1.91 cm or 4.84 cm^2. As previously discussed, standard monochrome television provides a resolution of about 350 horizontal elements and 350 to 400 vertical elements. The writing rate horizontally for a television picture is 15,750 lines per second or 63.5 microseconds per line. The time useful for writing the horizontal picture information is a minimum of 52.1 microseconds, the remaining line time being used for horizontal synchronization purposes. Thus, the time that a writing beam having 350 horizontal resolution elements contributes to the energy at a horizontal position on a line is given approximately by the active line time divided by the number of resolution elements which is 52.1/350 or 0.15 microseconds. The beam contributes to each resolution cell of the image at a given horizontal position for the above time interval. A scanning beam would have to deliver the required energy to a given resolution cell during this time interval over the area covered by the beam. The required energy density to obtain a contrast of 100:1 is 550 ergs/cm^2. The area of the spot produced by the beam with the above resolution capabilities is 3.5×10^{-5} cm^2. The power required to excite a spot on the input device to this level would therefore be $550 \times 5.3 \times 10^{-5}/0.15 \times 10^{-6}$ which gives 1.94×10^5 ergs/sec or 19.4 milliwatts. This power level at the writing wavelength of 440 nm is available in HeCd lasers. HeCd lasers are commercially available with CW power levels of 100 mW [5-8].

While the lasers with adequate power to write on the PROM at television rates are available, deflection of the laser beam at television horizontal rates presents some problems. Acousto-optic deflection systems have been constructed [5-9] which operate at the television horizontal deflection rates, but these systems are complex and operation of such systems in a spacecraft environment is questionable because of the volume and complexity of these devices. Vertical deflection may be accomplished with galvanometer driven mirrors. Galvanometer response is limited to frequencies below 1 kHz.

Use of laser writing on a device such as a PROM may be more attractive at scan rates encountered with multispectral scanners. Typically these devices generate horizontal image lines at a slower rate. The ERTS MSS generated horizontal lines in groups of six adjacent lines during an active scan and retrace time of 73.4 milliseconds. The oscillating mirror produced a scan and retrace cycle which was triangular in shape. Scanning of a laser beam to write on the PROM at this rate could be accomplished using a galvanometer driven mirror. Since the lines are generated in groups of six adjacent lines per scan, a problem exists in writing the scan lines on the PROM since only one line at a time can be written with a single laser beam and amplitude modulation system. A single laser with beam splitters and multiple modulators presents a possible solution to this problem. Otherwise, provision for storage of the scanned lines in parallel and readout to the writing laser beam as serial data would have to be provided. The power requirement of the writing laser beam would be less than that for television information because of the increased resolution of the MSS and the reduced sweep rate.

Placing an additional laser on board a spacecraft to provide the writing function of the PROM is undesirable from the standpoint of equipment complexity, and related power supply requirements. Other possibilities exist for writing on the PROM by making use of CRT or storage tubes, which may result in simplified equipment at the expense of data processing rates.

Miniature cathode ray tubes are available with a one inch square usable screen area and with a resolution of 0.001 to 0.002 inches. The Hughes H-1320 is an example of such a CRT. The screen brightness of the tube is 150 foot-lamberts. Phosphors available in the blue spectral region are of medium short persistence. The P-5 and P-11 phosphors decay to 10 percent of their peak value in approximately 26 and 80 microseconds respectively. Assuming that the light output of the CRT decays linearly with time and that the light output is proportional to the area under the brightness versus time curve, the light output of a P-11 phosphor would be approximately 75/2 = 37.5 foot-lamberts during the 80 microseconds required for the phosphor to decay. This brightness is equivalent to approximatley 1.2×10^{-4} watts per cm^2 radiated into 2π steradians. Using fiber optics, the light from the CRT could be coupled to the PROM with very little loss. Fiber optic coupling is attractive in this case since both the CRT active phosphor area and the PROM active area are the same size. The light available from the CRT amounts to an energy of 0.1 $ergs/cm^2$ per picture frame. To obtain the desired energy of 550 $ergs/cm^2$ would require over 5000 frames or 1667 seconds or 2.8 minutes.

A storage tube can provide a continuous light output over a much longer time interval, once the image is scanned on the tube. The light output of a storage tube with a brightness of 1000 foot-lamberts is 3.17×10^{-3} W/cm^2, which is equivalent to 5.040 $ergs/cm^2$ sec. To obtain the energy of 550 $ergs/cm^2$ required by the PROM to give a contrast ratio of 100:1 would require 109 milliseconds of exposure. This assumes that all of the light is collected and applied to the PROM. The resolution of the storage tubes is not such that the desired resolution may be obtained in a 1:1 size relationship with the PROM. As discussed for the Liquid Crystal Modulator, a large storage tube must be used in order to obtain the resolution approaching monochrome television standards. Using the optical system discussed for the Liquid Crystal Modulator with a demagnification of 4:1 the amount of light collected would be 376 $ergs/cm^2/sec$ and would take 1.5 seconds to expose the crystal to the desired energy.

Provision for erasure of the PROM must also be made. Erasure is accomplished by exposing the PROM to white light generated by a Xenon flash tube. Timing of the erase pulse and power supplies for the flash tube must be provided by the electronic system.

Selection of the specific real time input device from the electronic standpoint involves trade-offs of several considerations. The Liquid Crystal Modulator has the advantage of a single low voltage power supply, and is a device constructed using thin film technology with the potential of reducing unit cost in production quantities. Its response and decay characteristics cause problems in writing an image on the device for optical processing. The contrast available with the Liquid Crystal Modulator is limited to about 100:1.

The PROM has better contrast (10^4:1), and has storage and integration capabilities. It requires power supplies in the range of several kilovolts which must be switched across the PROM. Erasure capabilities must also be provided.

Although the Liquid Crystal Modulator and the PROM appear at this time to be the best devices for real time input to an optical processor, both are in the fairly early stages of development. The realization of a real time optical processor is highly dependent on some form of real time input device. Because of the complex nature of these devices, and the many variables in the electronic to optical interface, specification of optical processor parameters before laboratory evaluation is considered a high risk.

VI. DIGITAL ANALYSIS OF OPTICAL PROCESSING

A. Introduction

In order to resolve several questions regarding optical processing, some digital modeling and analysis of optical processing was carried out. Although the studies were limited in scope, the results are helpful in gaining insight into the performance of optical processors.

B. Correlation Detection

The following description of the mathematics of joint transform correlation was extracted from Nisenson and Sprague [6-1]. The input object function is of the form

$$o(x,y) = g(x - a,y) + h(x + a,y), \tag{6-1}$$

where $o(x,y)$ is the object amplitude, $g(x,y)$ and $h(x,y)$ are the amplitudes of the two transparencies to be cross-correlated, and 2a is their center-to-center separation in the input plane. The amplitude in the optical Fourier transform has the form

$$F[o(x,y)] = G(u,v)e^{iua} + H(u,v)e^{-iua}, \tag{6-2}$$

where $F[o(x,y)]$ is the transform of $o(x,y)$, $G(u,v)$ and $H(u,v)$ are the transforms of $g(x,y)$ and $h(x,y)$, respectively, and u and v are the Fourier transform coordinates. The square modulus of the transform is

$$\begin{aligned} |F[o(x,y)]|^2 = \; & |G(u,v)|^2 + |H(u,v)|^2 + G(u,v)\, H^*(u,v)e^{2iua} \\ & + G^*(u,v)\, H(u,v)e^{-2iua} \quad . \end{aligned} \tag{6-3}$$

Assuming recording on the linear region of the amplitude transmittance versus exposure curve and unit magnification, retransformation yields a final image $i(x',y')$ given by

$$i(x',y') = g(x',y') * g(x',y') + h(x',y') * h(x',y')$$

$$+ g(x',y') * h(x' - 2a,y') + g(x',y') * h(x' + 2a,y') \quad , \qquad (6\text{-}4)$$

where * denotes the correlation operation. The last two terms are the desired object cross-correlation functions. They are shifted off-axis by a distance 2a and so separated from the other image terms.

A digital simulation of optical processing was constructed to investigate the behavior of the correlation terms in (6-4). This mode used an N x N array to represent the object plane, with the left half of the plane containing one object and the right half of the plane containing the other. A two-dimensional fast Fourier transform (FFT) was used to produce the frequency spectrum, the squaring operation shown in (6-3) was carried out, and the result retransformed to produce the correlation plane output. The results were plotted using a three dimensional plotting technique.

Initial runs were made using a 64 x 64 array. Figure 6-1 shows a plot of the object plane with two rectangular blocks oriented the same. These are positioned so that they represent identical "pictures". The spacing, 2a, between the objects was chosen to be N/4 (a = N/8), so that the correlation function produced would range from -4a to +4a. The objects in Figure 6-1 have dimensions of 12 elements x 4 elements in the input array. The amplitude was arbitrarily set at 1.0; the border elements have amplitudes 0.5 to satisfy a requirement in FFT processing in order that extraneous frequencies not be produced.

A linear plot of the correlation function produced by these objects is shown in Figure 6-2. The linear plots are normalized to a peak value of 1.0, and the base plane represents amplitude 0. A logarithmic plot of the same correlation function is shown in Figure 6-3, with the peak normalized to 0 dB, and the base plane representing -30 dB.

Figures 6-4 through 6-6 show a similar set of plots for one of the rectangles turned 90° with respect to the other. Note that although the cross-correlation is reduced, it still has a significant value.

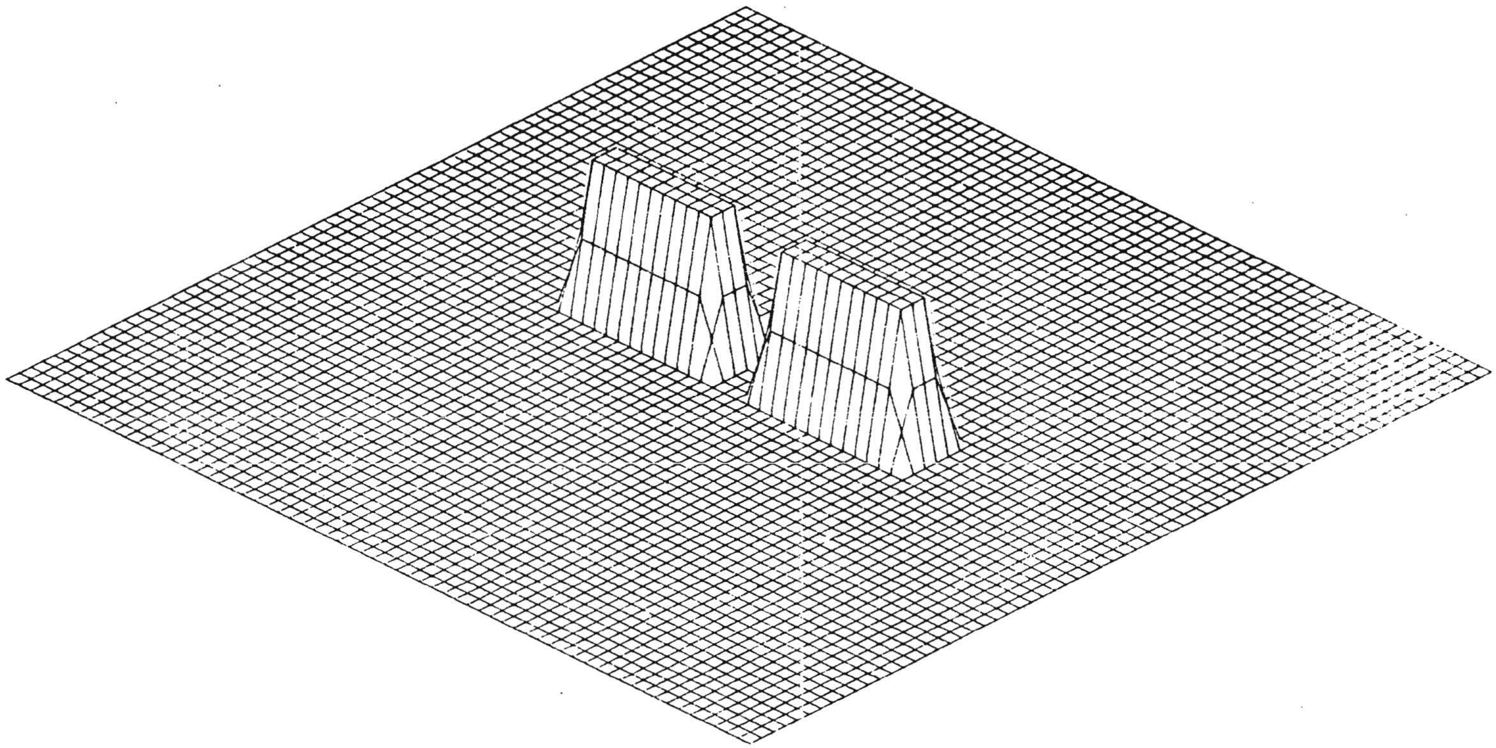

Figure 6-1. View of Object Plane with Two 12 x 4 Rectangular Blocks with Identical Orientation

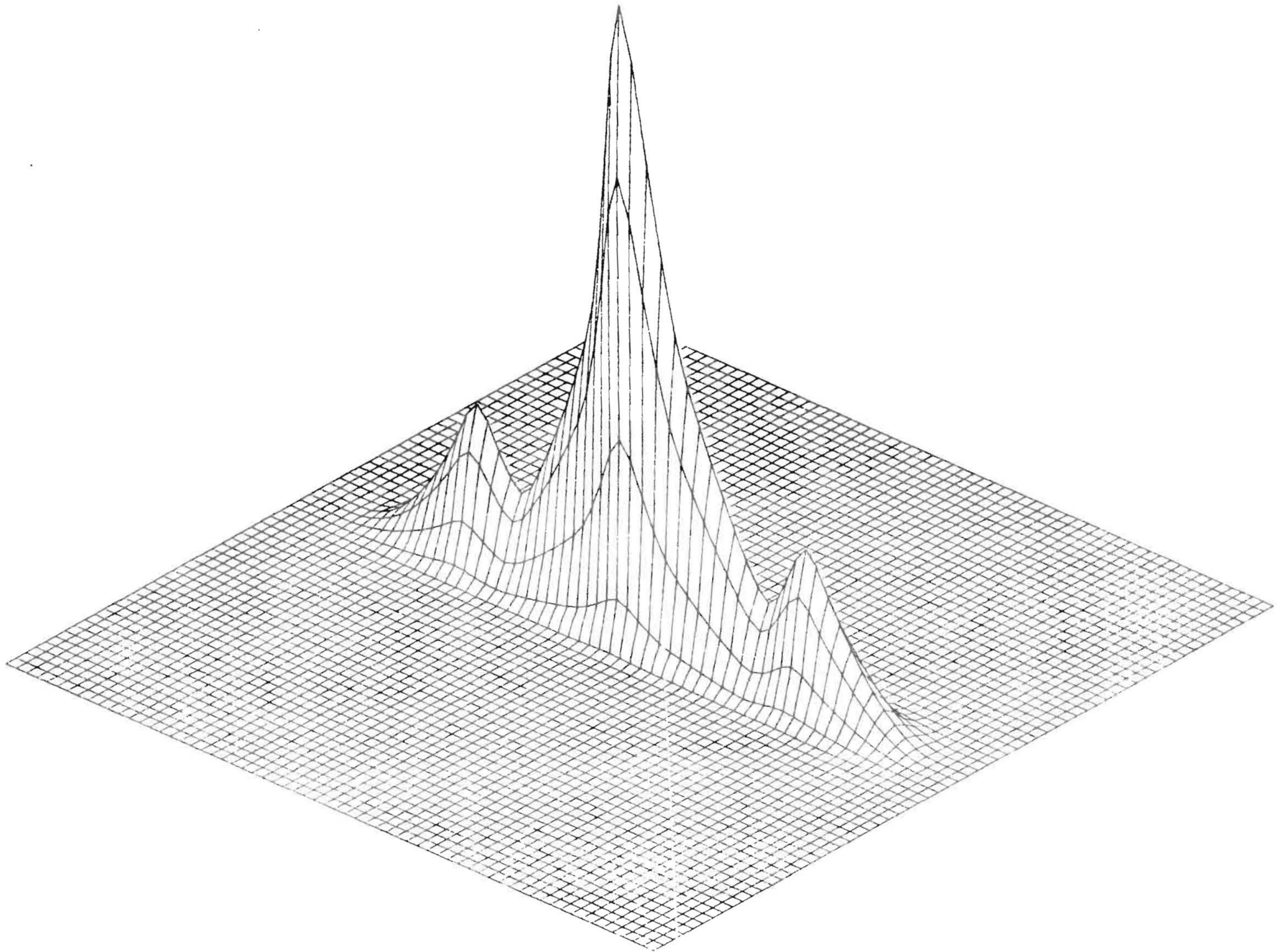

Figure 6-2. Linear Plot of the Correlation Function Produced by the Objects in Figure 6-1.

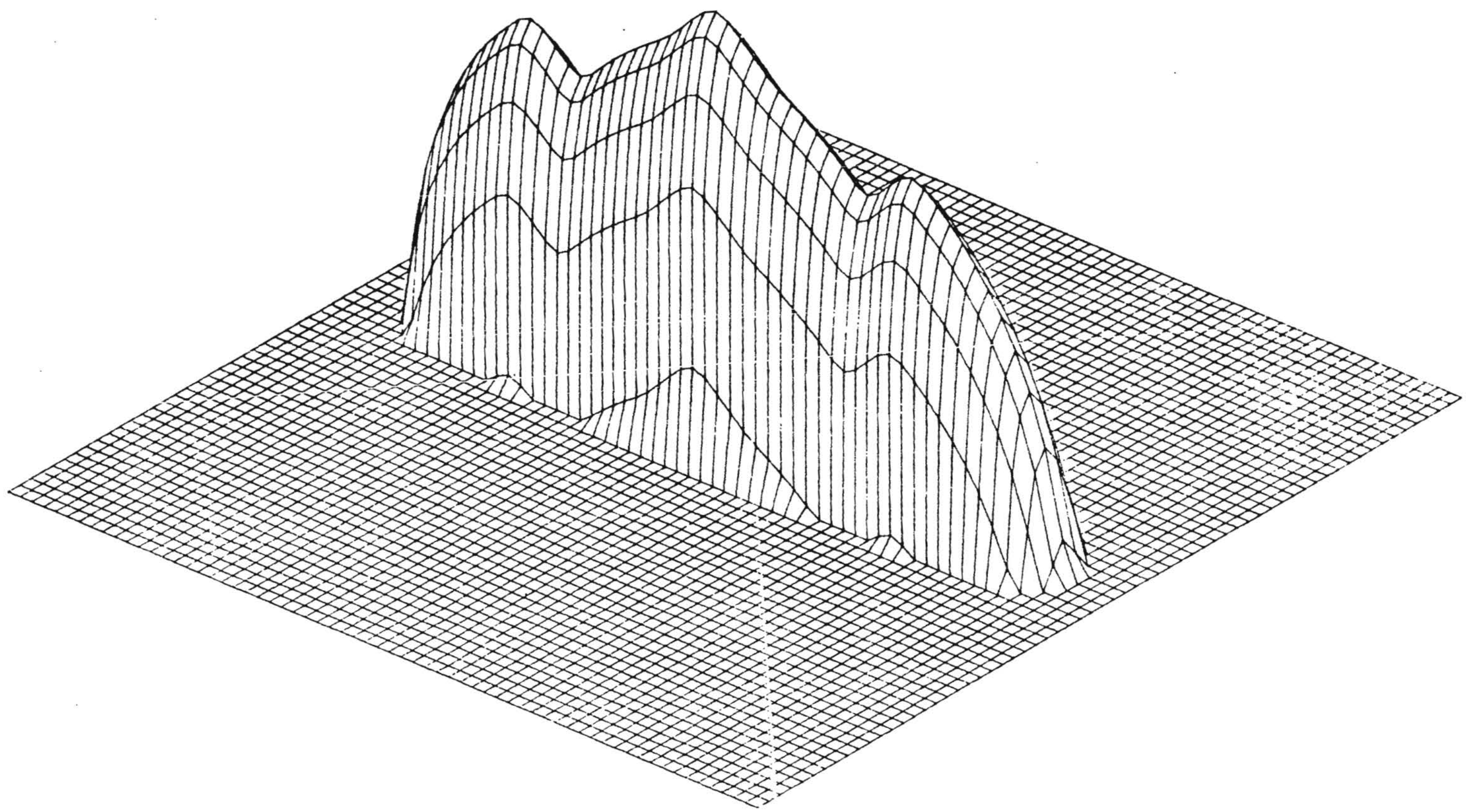

Figure 6-3. Logarithmic Plot of the Correlation Function Produced by the Objects in Figure 6-1.

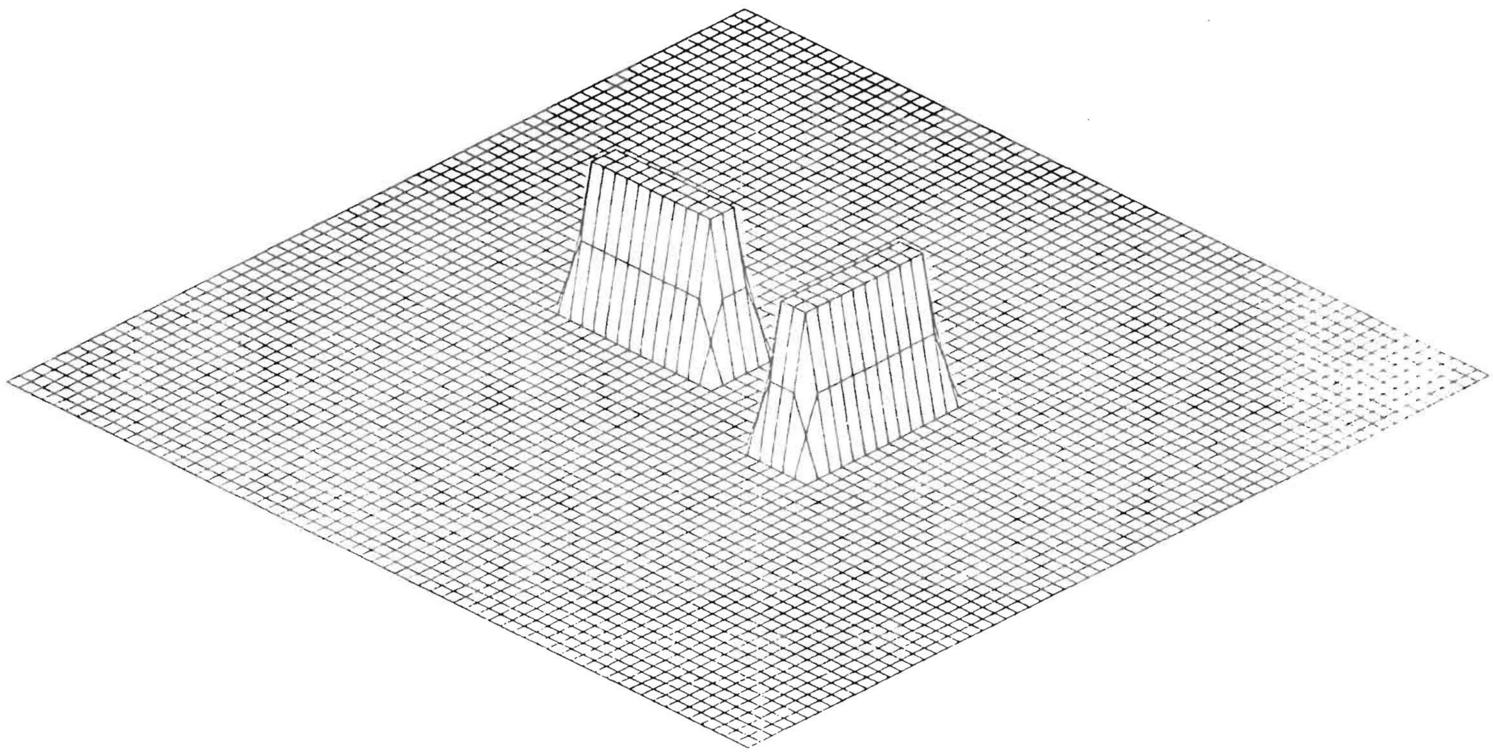

Figure 6-4. View of Object Plane with Two 12 x 4 Rectangular Blocks Oriented Orthogonally.

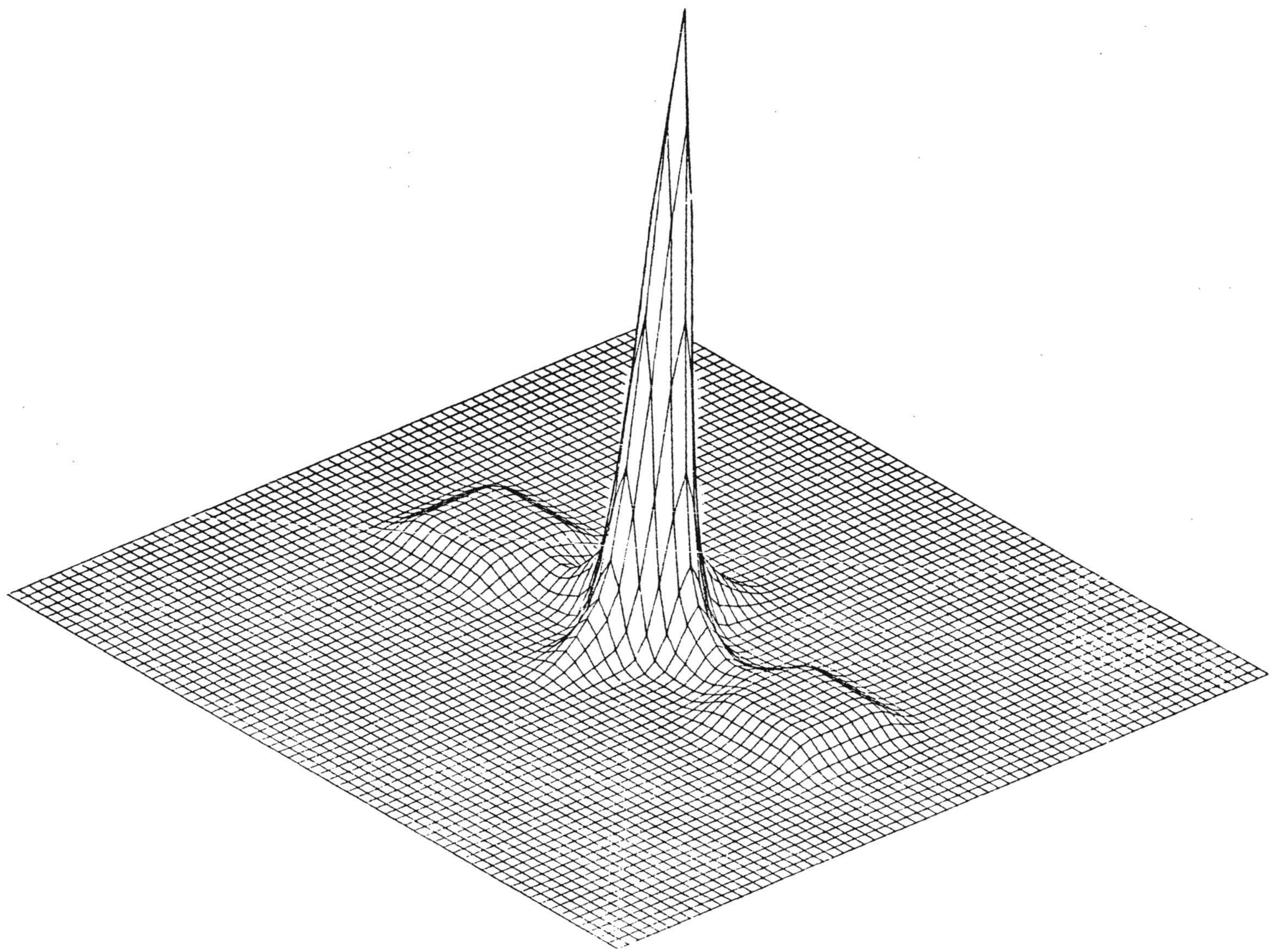

Figure 6-5. Linear Plot of the Correlation Function Produced by the Objects in Figure 6-4.

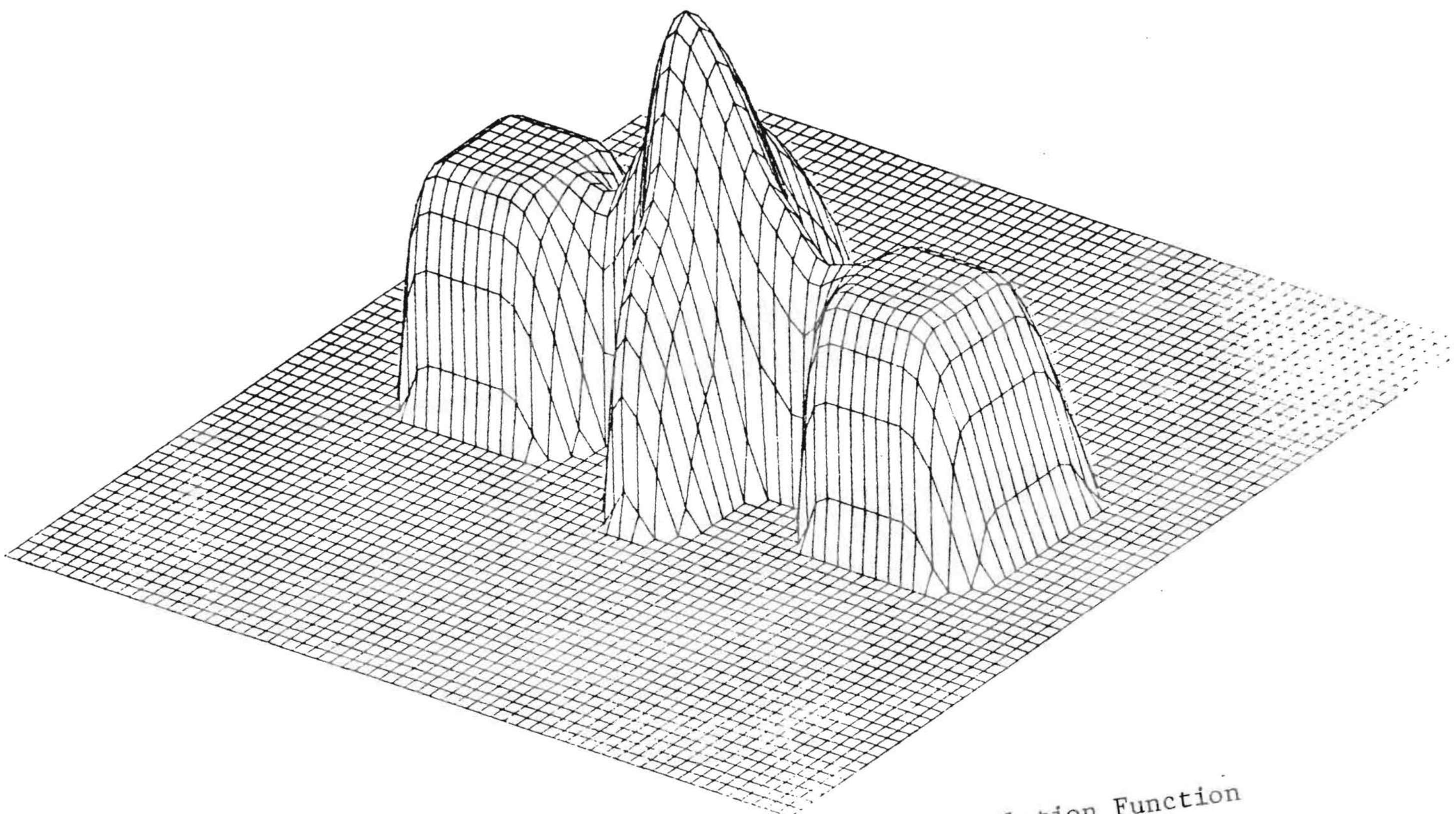

Figure 6-6. Logarithmic Plot of the Correlation Function Produced by the Objects in Figure 6-4.

The object spacing chosen for these initial runs produced some overlap in the auto-correlation and cross-correlation terms (evidenced in Figures 6-2, 6-3, 6-5 and 6-6 by the fact that the correlation plot does not drop to zero between the center and side peaks). It was evident that it would be desirable to locate the objects further apart. The simulation was restructured with a 128 x 128 array with an object-to-center spacing of a = 16 array elements. Each "picture" was then restricted to a 16x16 section centered at the object locations. The plotting routine was modified to plot a reduced central sector, and to plot only every other element from this sector. These changes were necessary to reduce plotting time. Figure 6-7 shows the layout of the array, with the dimensions in array elements.

This modified simulation was run with 16 x 2 rectangles representing the picture elements oriented in 3 different ways. Figure 6-8 shows the object plane when both rectangles are parallel to the axis connecting the two pictures. A linear plot of the correlation function is shown in Figure 6-9, and a logarithmic plot in Figure 6-10. Similar plots are shown in Figures 6-11 through 6-13 for one of the objects turned perpendicular to the axis. A third set of plots are shown in Figures 6-14 through 6-16 with both objects located perpendicular to the axis.

The correlation plots from the above runs suggested strongly that the major effects of the process could be determined simply by examining the correlation function along the horizontal axis, hence studies using one-dimensional arrays and FFT's would be informative. Since the capability to operate with two-dimensional arrays was so limited (128 x 128 is the maximum with available software), a one-dimensional simulation was constructed. Figure 6-17 shows the correlation function produced when object functions consisting of idential square pulses were correlated. Note the agreement between Figure 6-17 and Figure 6-9.

This one-dimensional simulation was then run with an object function consisting of four pulses of different widths and spacings as shown in Figure 6-18 (the figure depicts only one of the two "objects"). With this function in both object locations, the correlation function shown in Figure 6-19 was generated. With the function as shown in the left object position,

(Note: Dimensions are in array elements. Dashed line shows area shown in 3-D plots.)

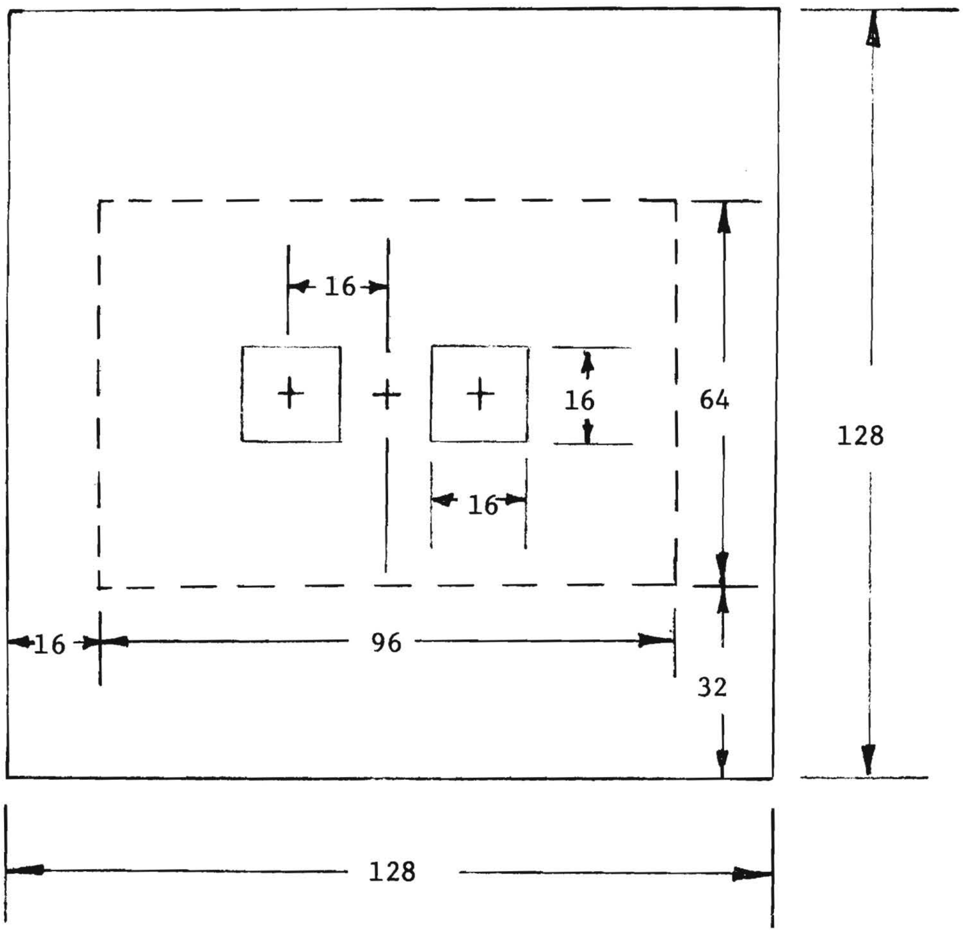

Figure 6-7. Layout of 128 x 128 Array.

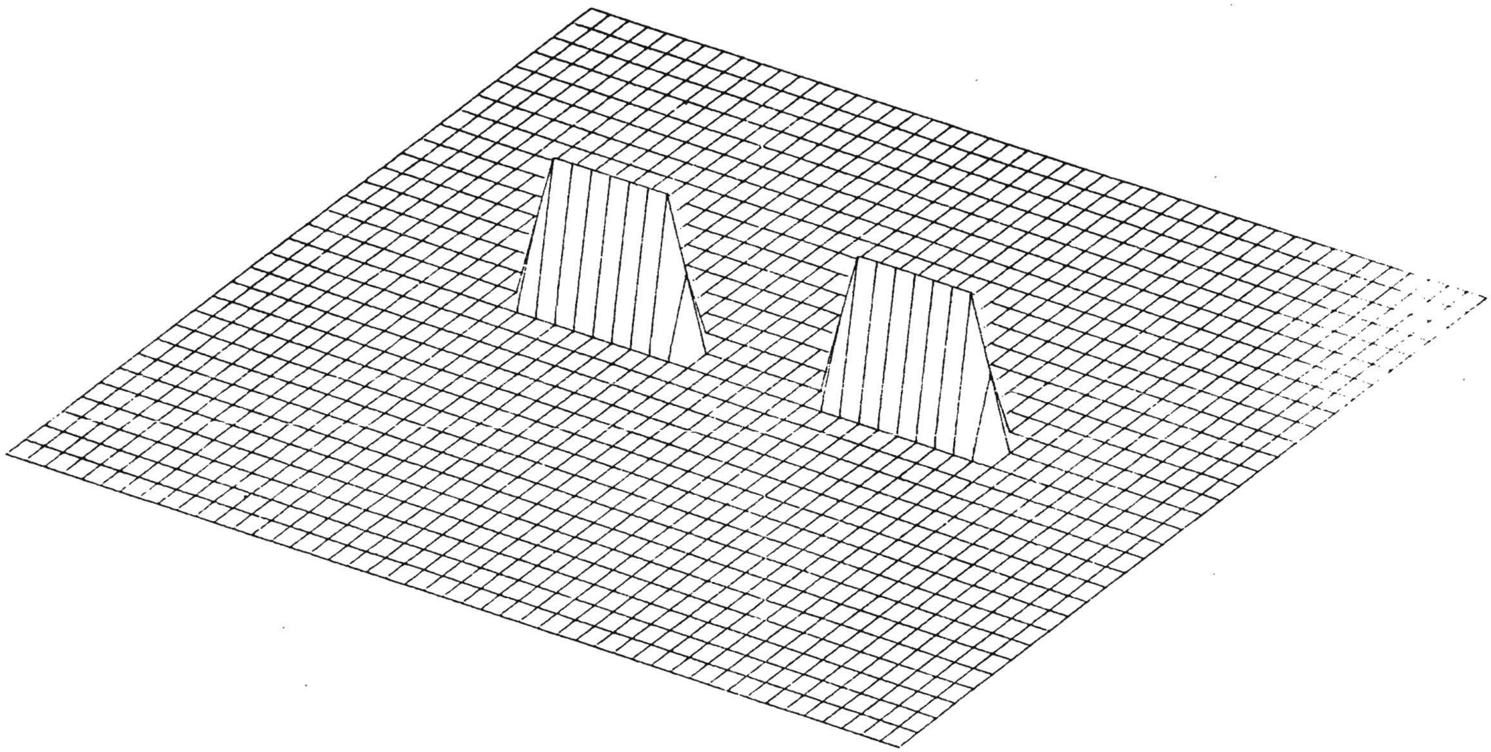

Figure 6-8. View of Object Plane with Two 16 x 2 Rectangular Blocks with Identical Orientation Having a Separation Which Eliminates Overlapping of Correlation Functions.

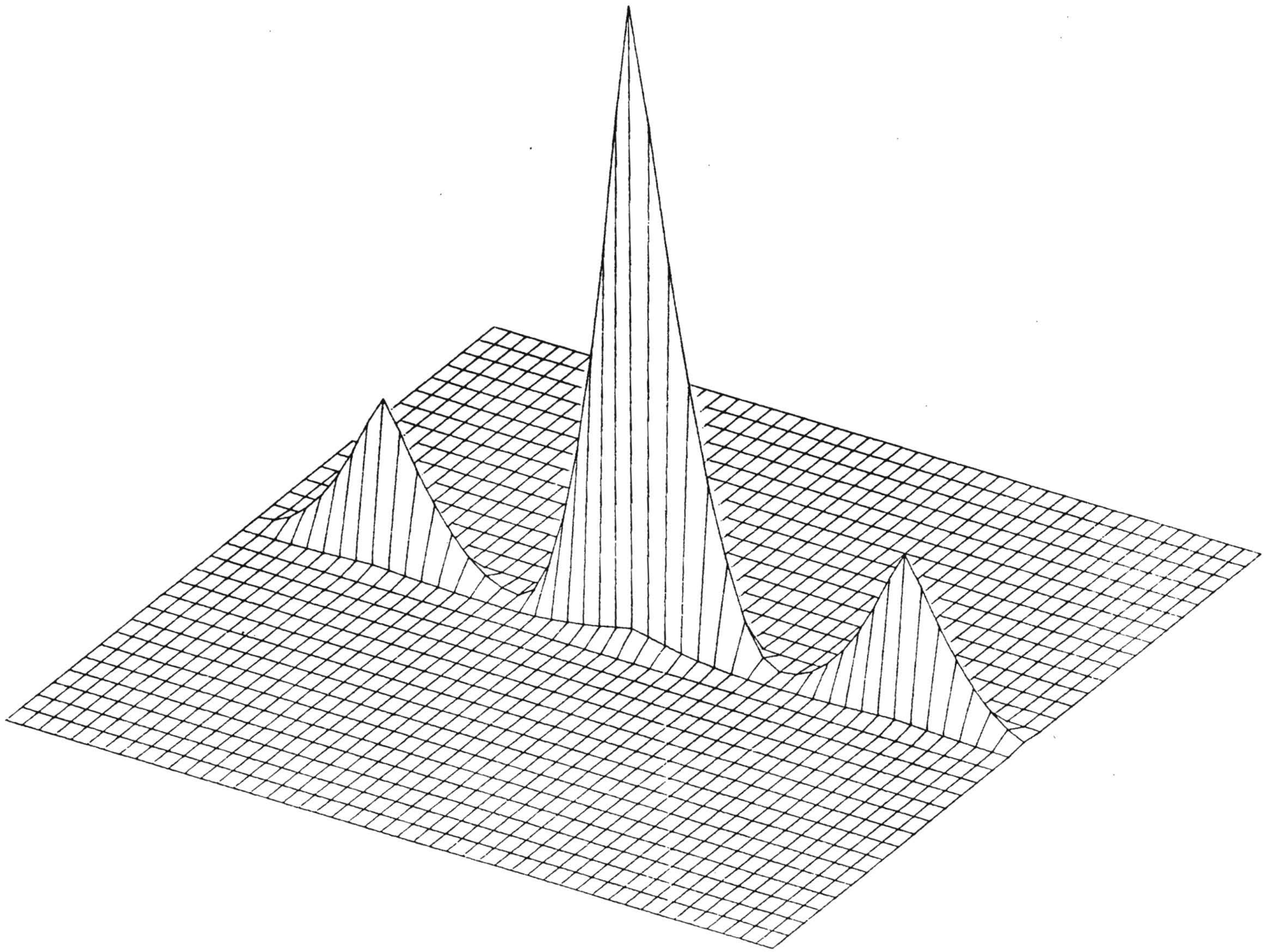

Figure 6-9. Linear Plot of the Correlation Function Produced by the Objects in Figure 6-8.

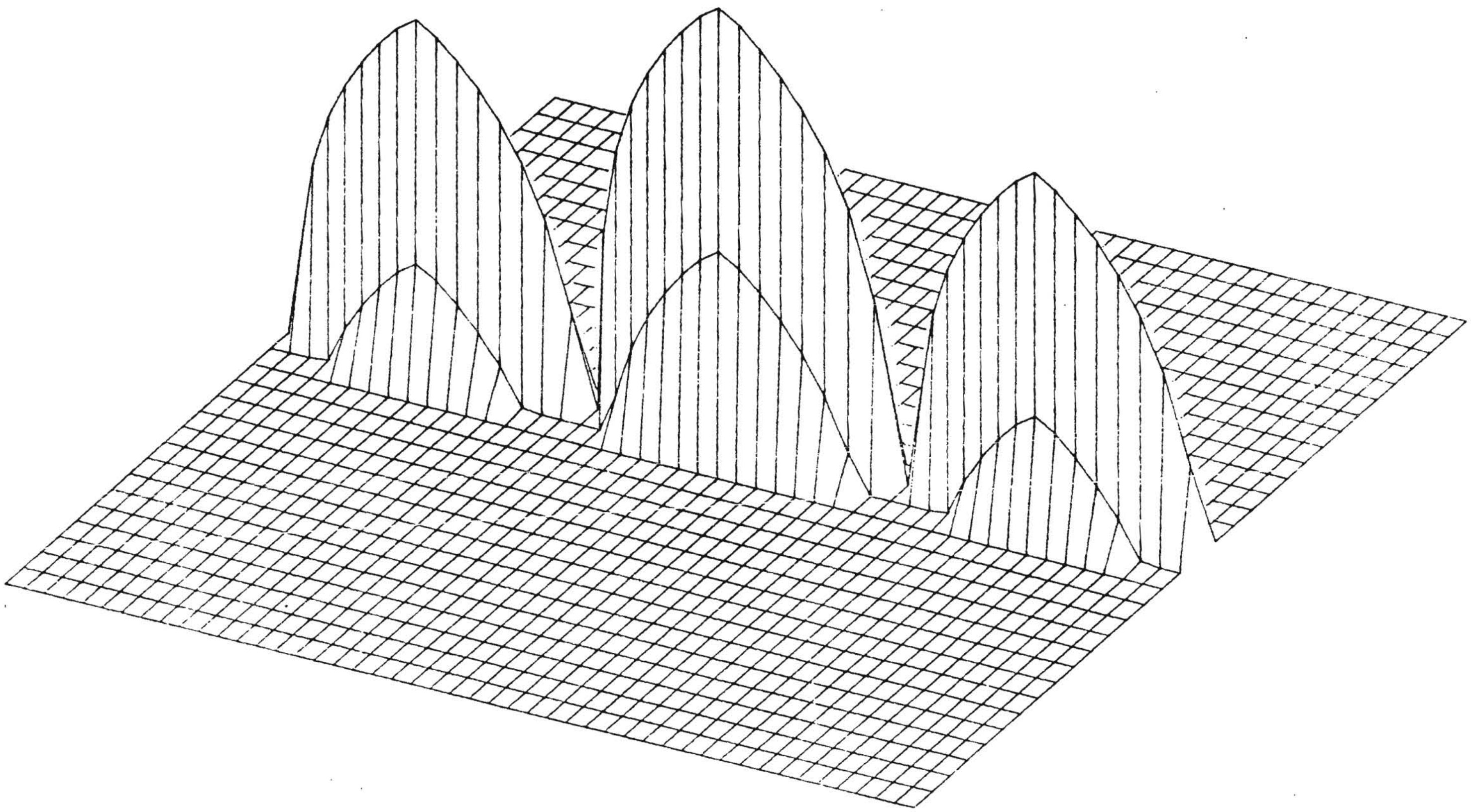

Figure 6-10. Logarithmic Plot of the Correlation Function Produced by the Objects in Figure 6-8.

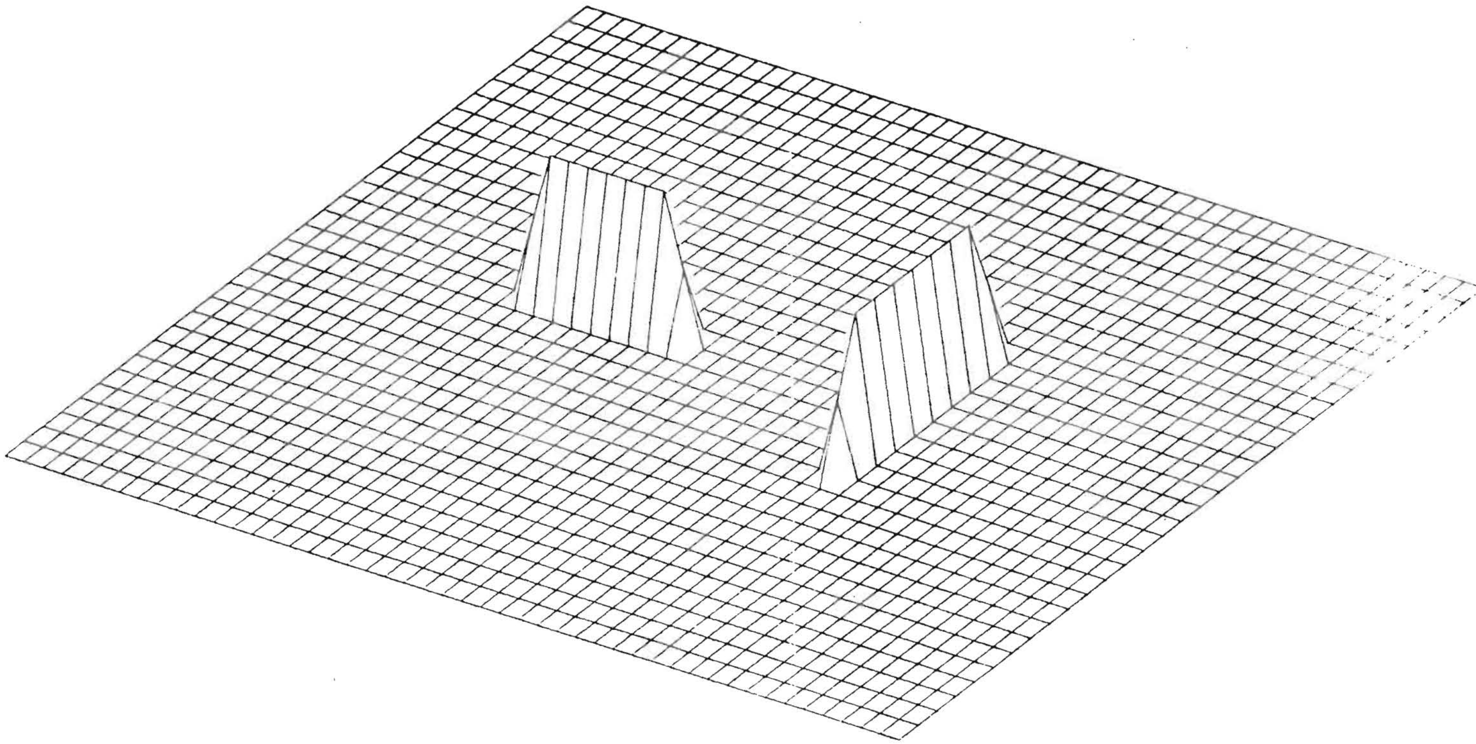

Figure 6-11. View of Object Plane with Two 16 x 2 Rectangular Blocks Oriented Orthogonally.

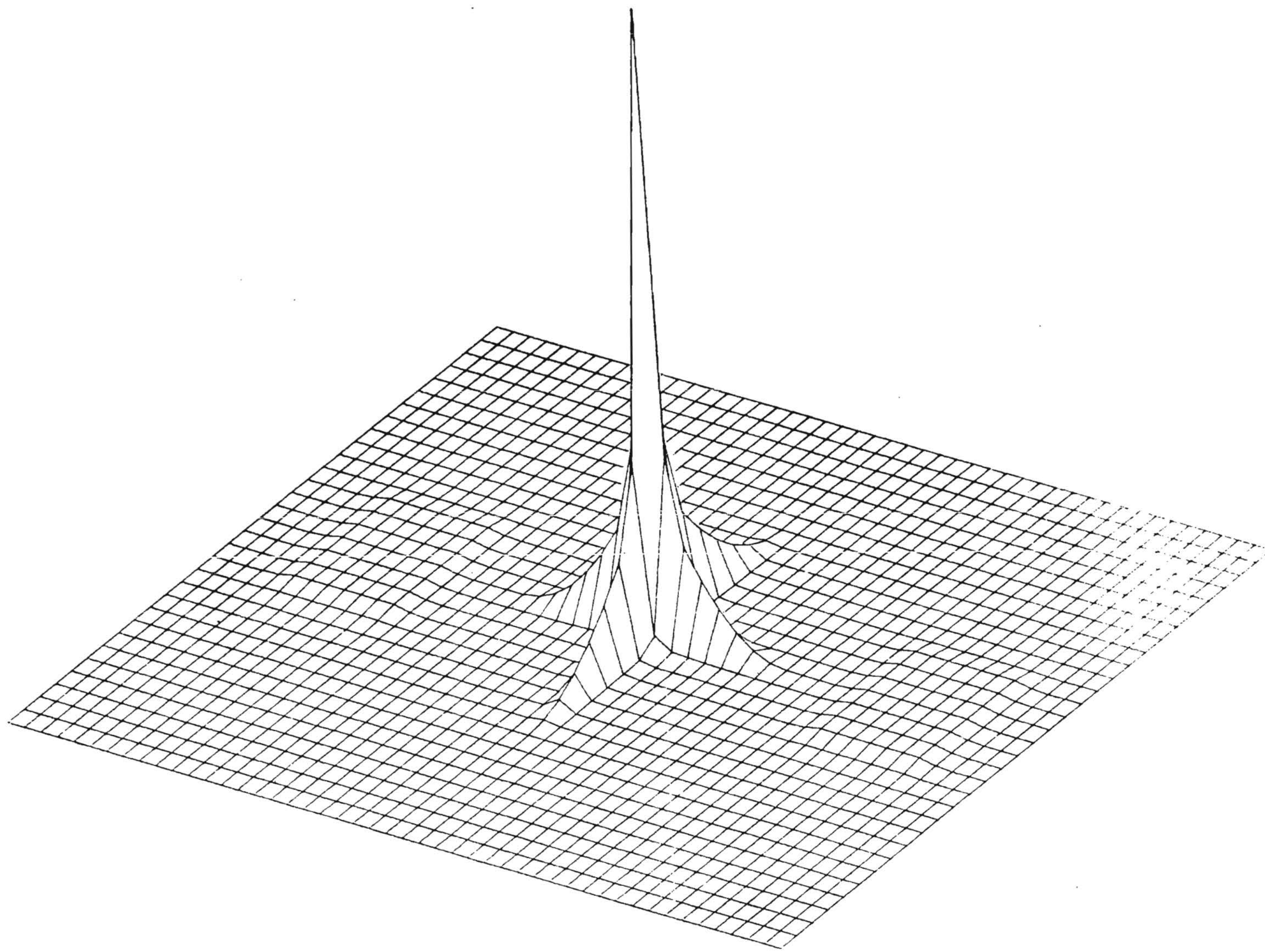

Figure 6-12. Linear Plot of the Correlation Function
Produced by the Objects in Figure 6-11.

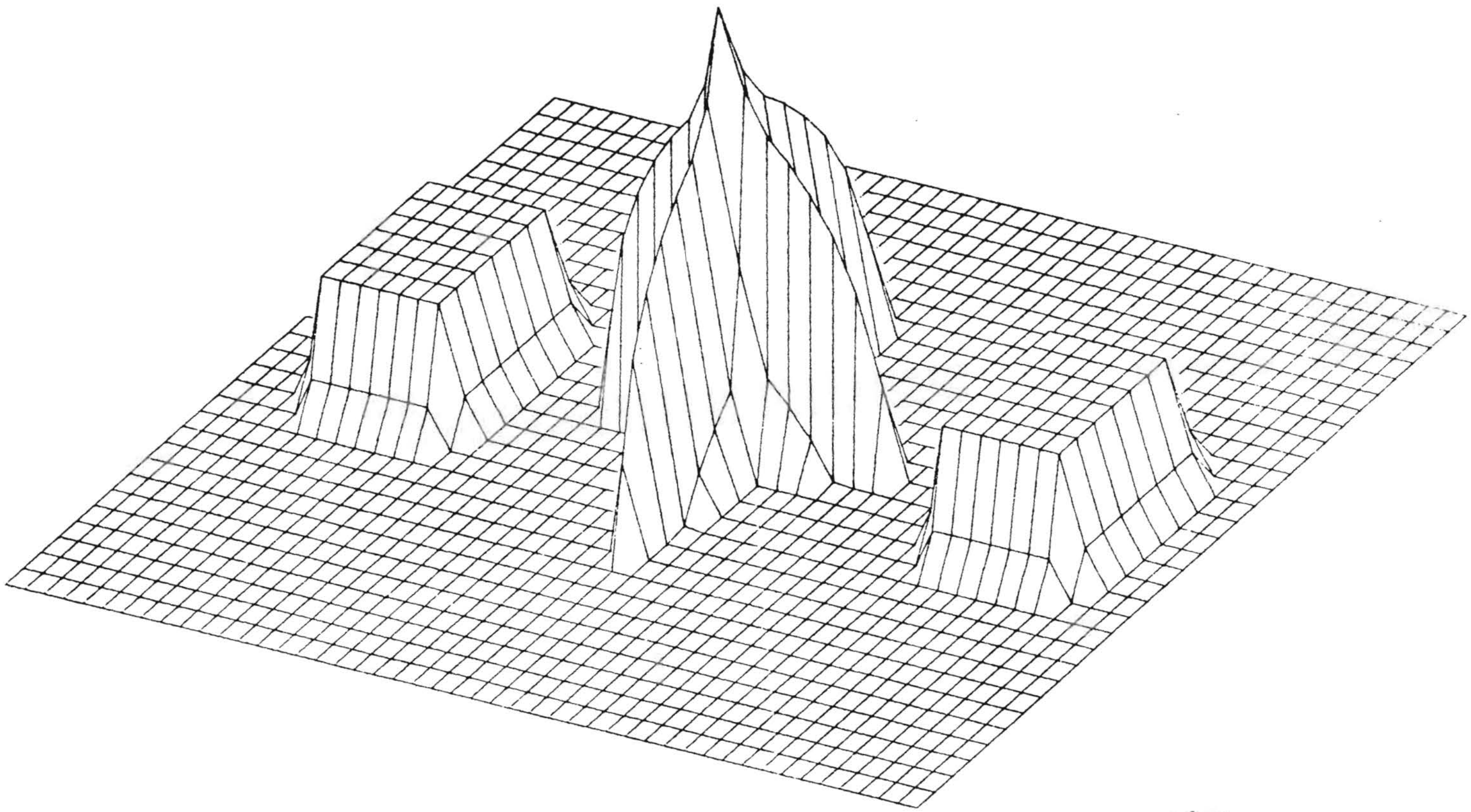

Figure 6-13. Logarithmic Plot of the Correlation Function Produced by the Objects in Figure 6-11.

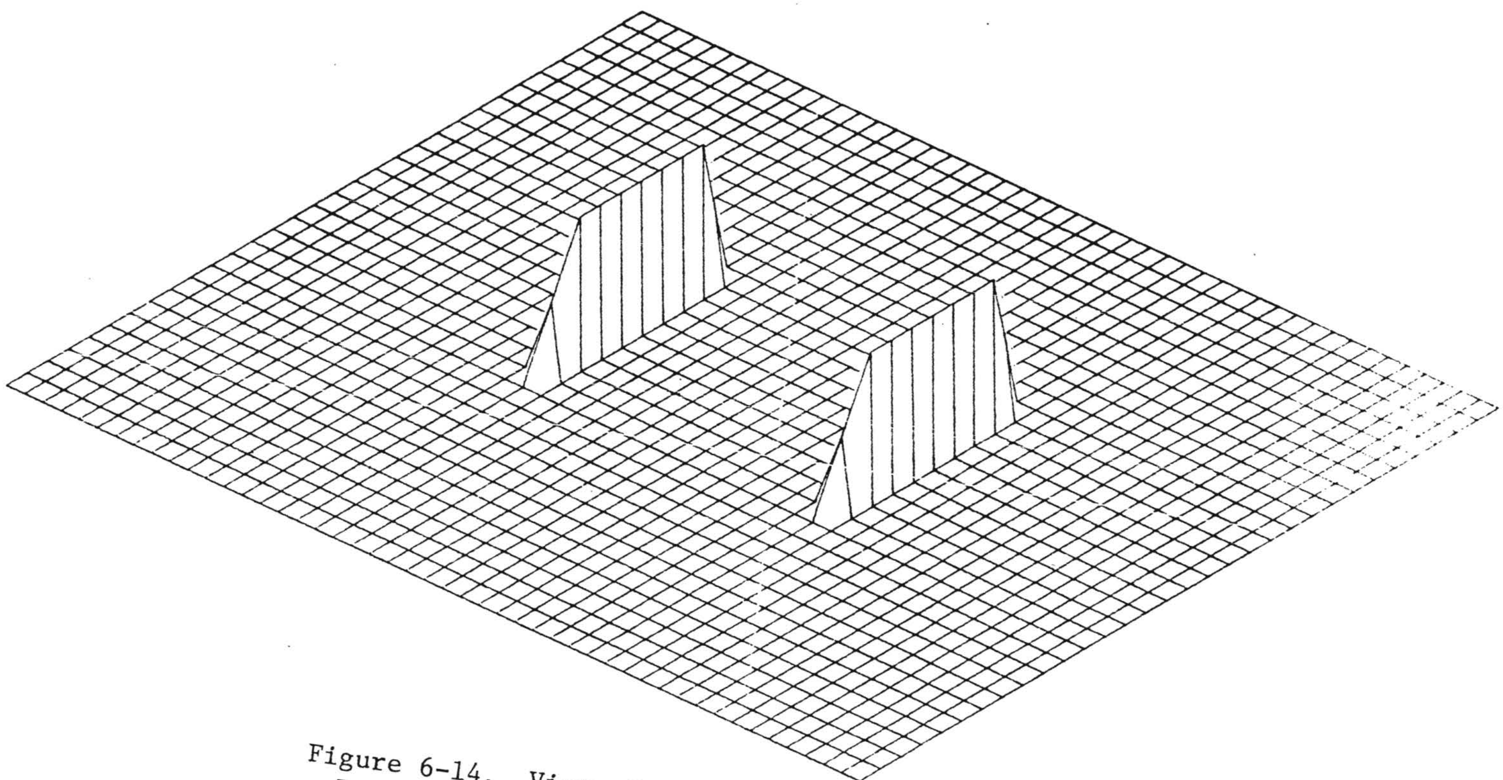

Figure 6-14. View of Object Plane with Two 16 x 2 Rectangular Blocks with Parallel Orientation.

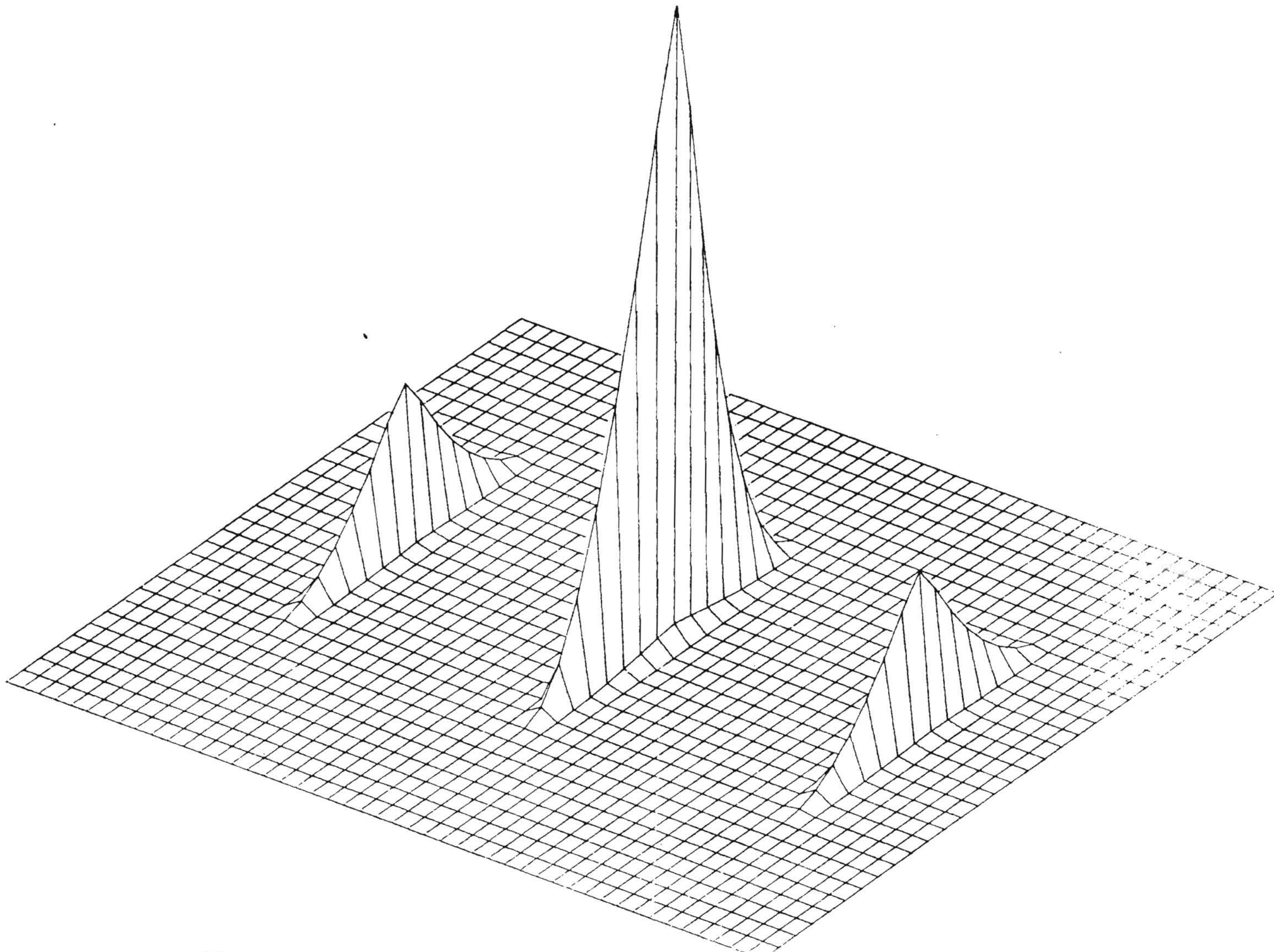

Figure 6-15. Linear Plot of the Correlation Function Produced by the Objects in Figure 6-14.

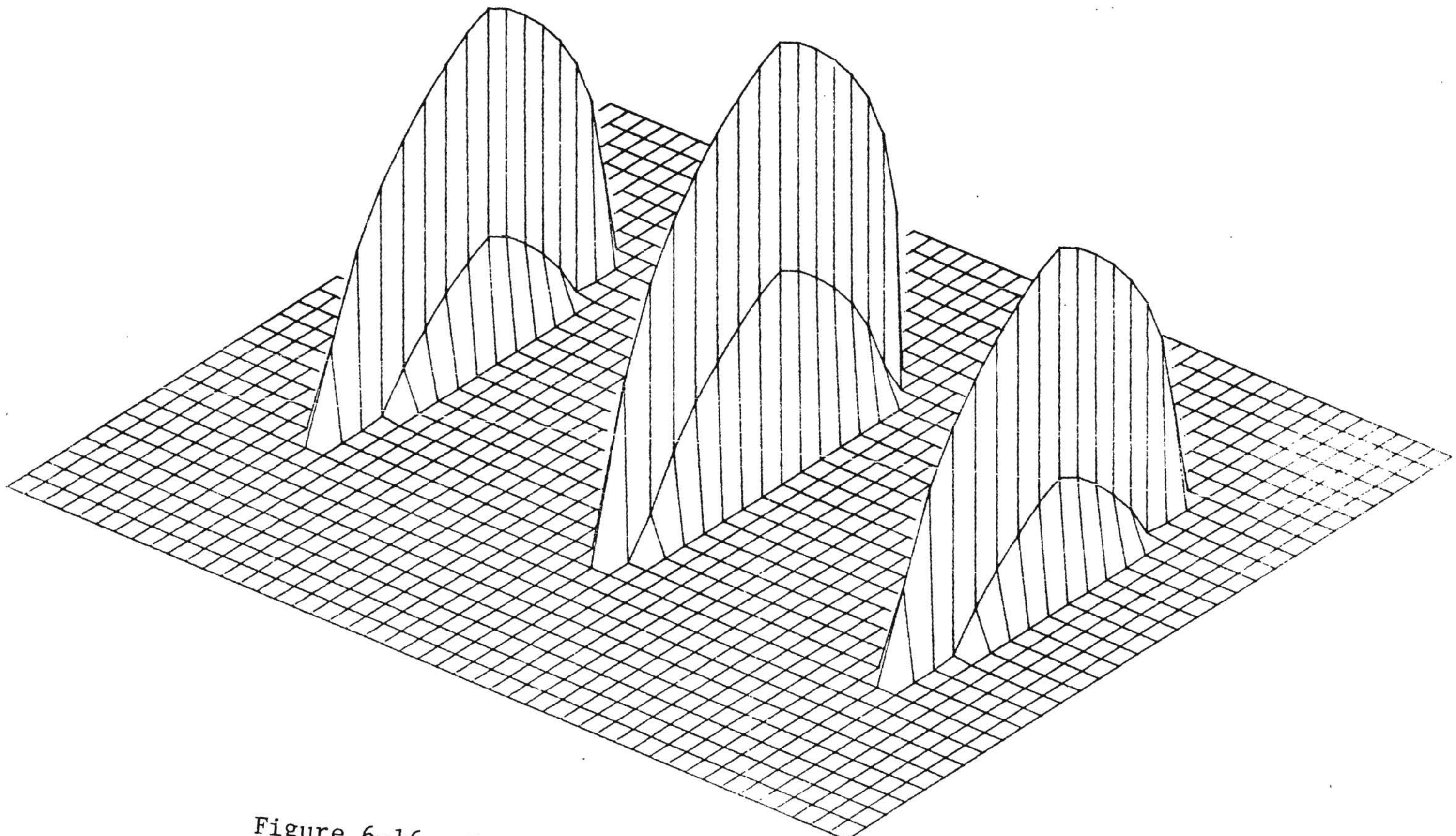

Figure 6-16. Logarithmic Plot of the Correlation Function Produced by the Objects in Figure 6-14.

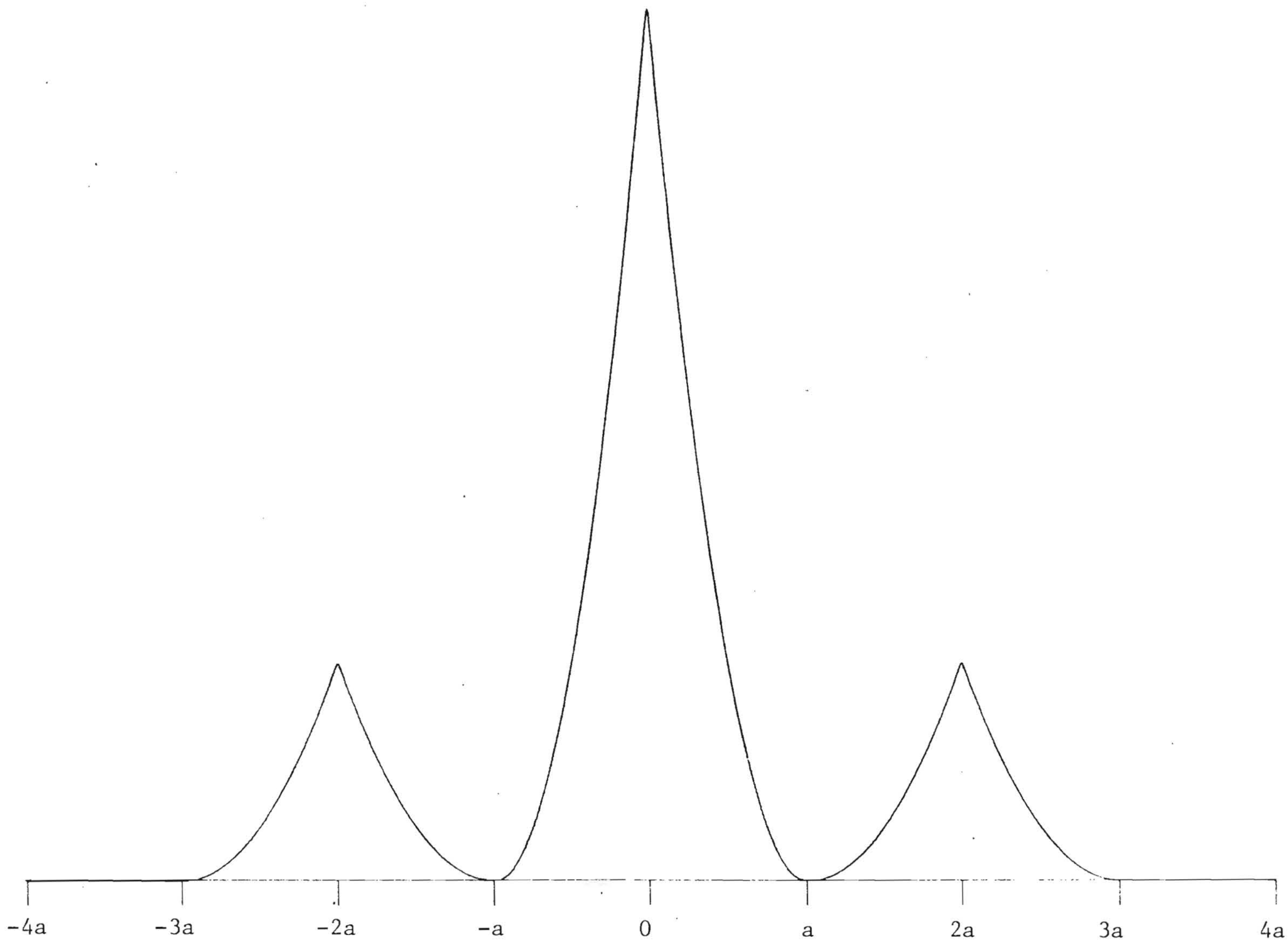

Figure 6-17. Single Dimension Correlation Function of Two Identical Square Pulses in Object Plane.

(Note: Dimensions in array elements)

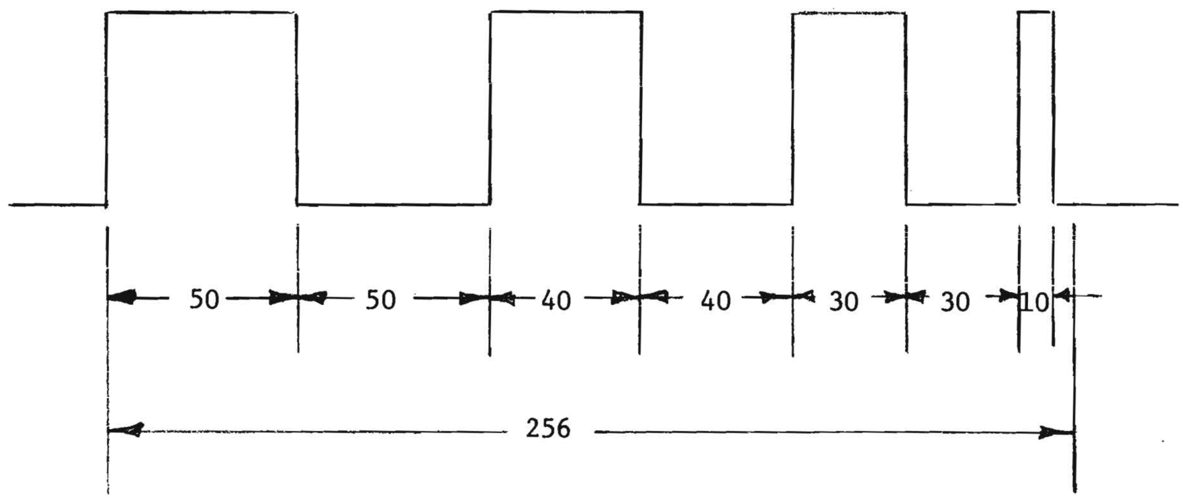

Figure 6-18. Object Function Used in One-Dimensional Simulation.

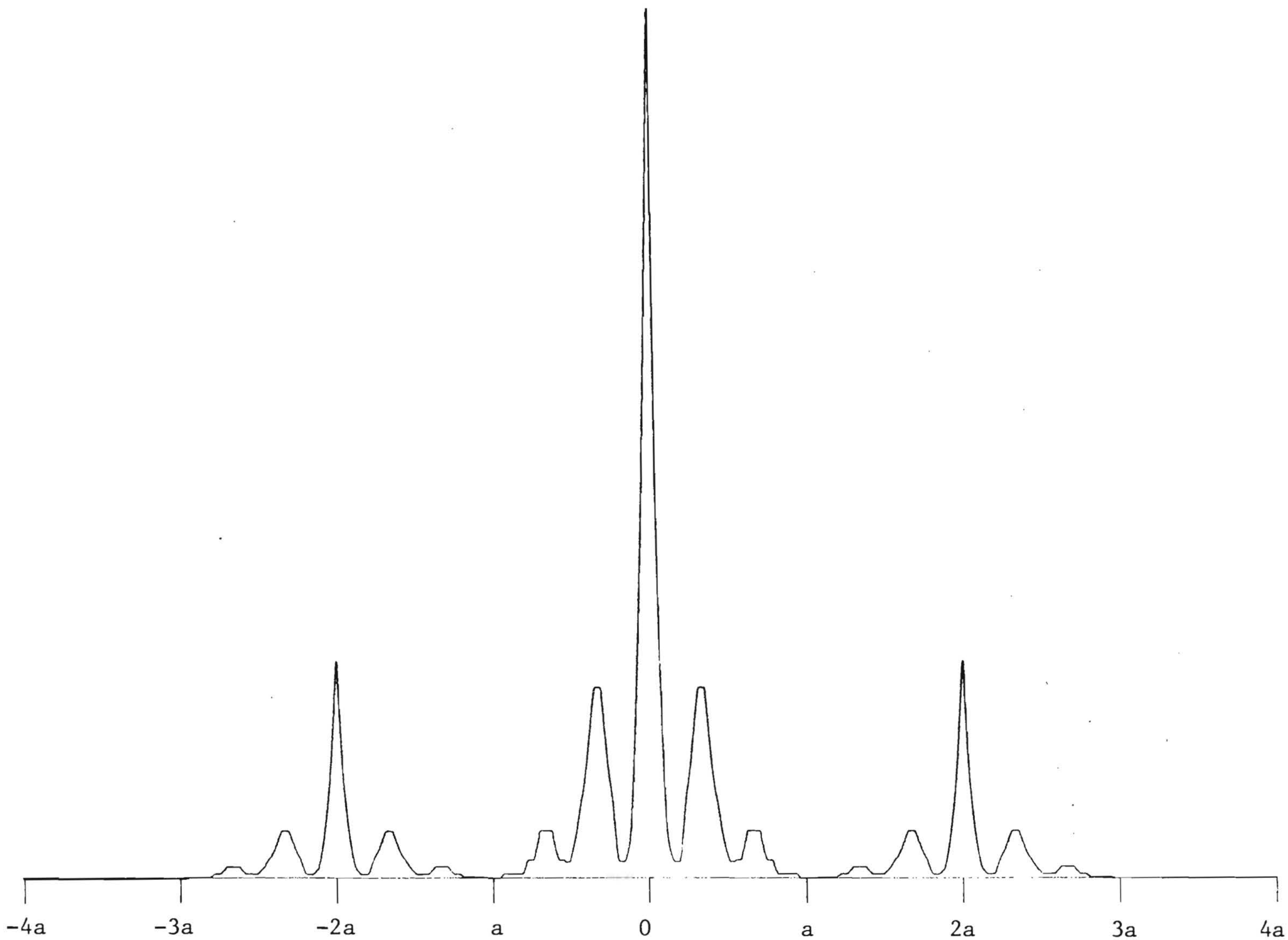

Figure 6-19. Single Dimension Correlation Function for Two Identical Object Functions as Shown in Figure 6-18.

and the object reversed (minor image) in the right object position, the correlation function shown in Figure 6-20 was generated.

The tic marks shown on the abscissa in Figures 6-19 and 6-20 are at spacing a, one-half the separation of the input objects. Thus the center of the cross-correlation functions are located at the second tic on either side of the center. Peaks at these points are quite evident in Figures 6-17 and 6-19. Note in Figure 6-20 that although the correlation function is relatively low at the 2a position, it is not zero and also has a prominent peak very near by. Since the object functions were mirror images, little correlation would be expected.

Although these simulation studies of optical correlation have been very limited in scope, they raise some questions about the application of optical processors to detecting correlation between pictures. Several investigators have produced "show pieces" of optical correlation by using simple geometric objects, but such studies leave many questions unanswered about optically correlating a picture of farm land with a picture of a forest. These studies carried out here show that the correlation function is not concentrated at a point, but is spread over an area. Furthermore, since optical correlation is an amplitude process, it is doubtful that the cross-correlation will exhibit zeros in the vicinity of the 2a point for any two general pictures (probably only amplitude variations will occur). Decisions about where to locate the correlation detector, how large an area it should sample, etc. are unanswered. For example, re-examine Figure 6-19 and 6-20 (which were also produced with geometric objects) and note the location of the peaks in the cross-correlation functions for perfect correlation in Figure 6-19 and decorrelation in Figure 6-20.

C. Window Function Effects

The liquid crystal input devices have several characteristics which make them attractive as candidates for object plane or filter plane input devices for a real time optical processor. Among these are size and power supply requirements. They do, however, have decay properties which make their use as real time input devices a subject of some concern. The characteristics of the liquid crystals have a definite impact on the interface electronics.

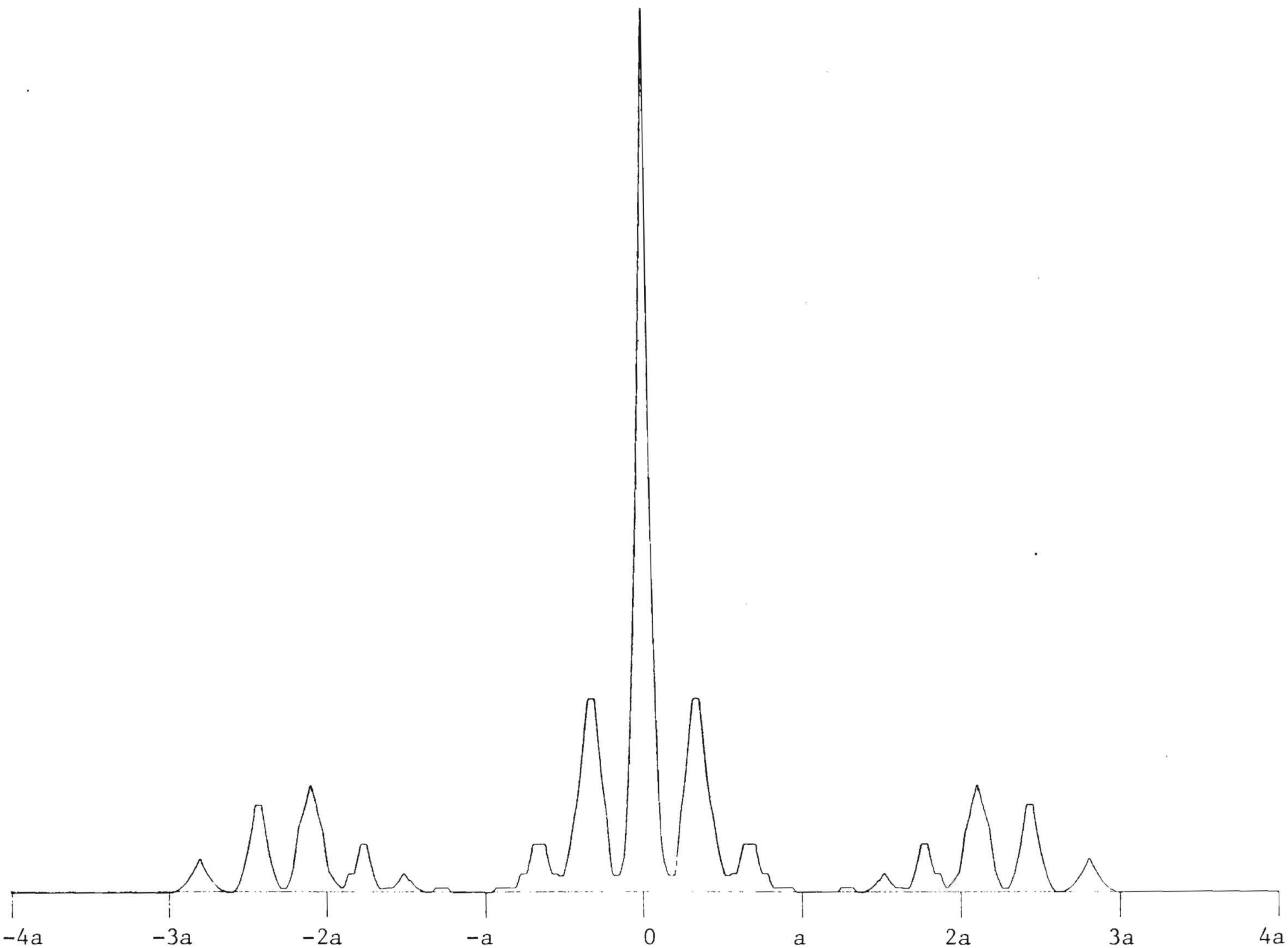

Figure 6-20. Single Dimension Correlation Function for two Object Functions, one Being the Pulses Shown in Figure 6-18 and the Other its Mirror Image.

The decay times associated with the liquid crystal device ranges from 10 to 30 milliseconds (possibly as short as several milliseconds). This time represents the decay of the image from full intensity to 10 percent of full intensity. This time, when compared to a television frame time of 33 milliseconds, is found to be a fraction of the television frame time.

It was this decay characteristic and its effect on the Fourier transform of input images which was of interest in this portion of the digital simulation. The simulation was carried out for single dimension input functions and used single dimension fast Fourier transforms to investigate the frequency domain characteristics of image function modified by various decay functions. The program is general in the sense that any decay function that can be described analytically or described by a table look-up technique may be applied to the object function. For the purpose of this investigation, because of the limited time available, only linear decay functions were applied to the object data. The complicated nature of the liquid crystal characteristics suggests that more complex decay functions would be required to accurately represent the characteristics of the liquid crystal.

Four examples of object functions were investigated to develop the analysis technique and to furnish some feeling for the effects of window functions on the transform plane data. These were (1) a square wave with a long period with respect to the interval over which the transform was taken, (2) a symmetrical square wave with a short period compared to the transform data interval (3) a nonsymmetrical square wave with a short period compared to the transform data interval, and (4) an arbitrary waveform which would more nearly represent a video waveform produced by data to be processed. For each of these cases the data presented are the object function along with its transform and the object function modified by the linear window function along with its transform. This provides the capability of comparing the transforms of the various data.

Figure 6-21 displays the "time waveform" which represents an input object function which is a square wave having two cycles in the transform interval selected. Figure 6-22 shows the Fourier transform of this input data on a linear amplitude scale. Figure 6-23 shows the frequency domain data on a

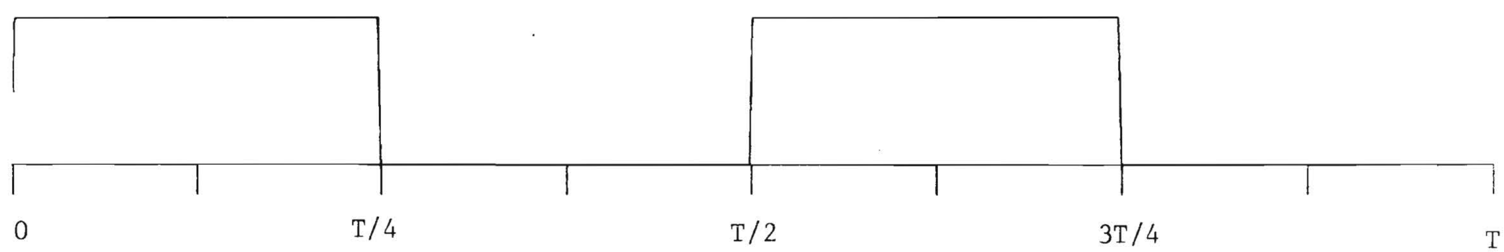

Figure 6-21. Input Object Function Consisting of a Two Cycle Square Wave.

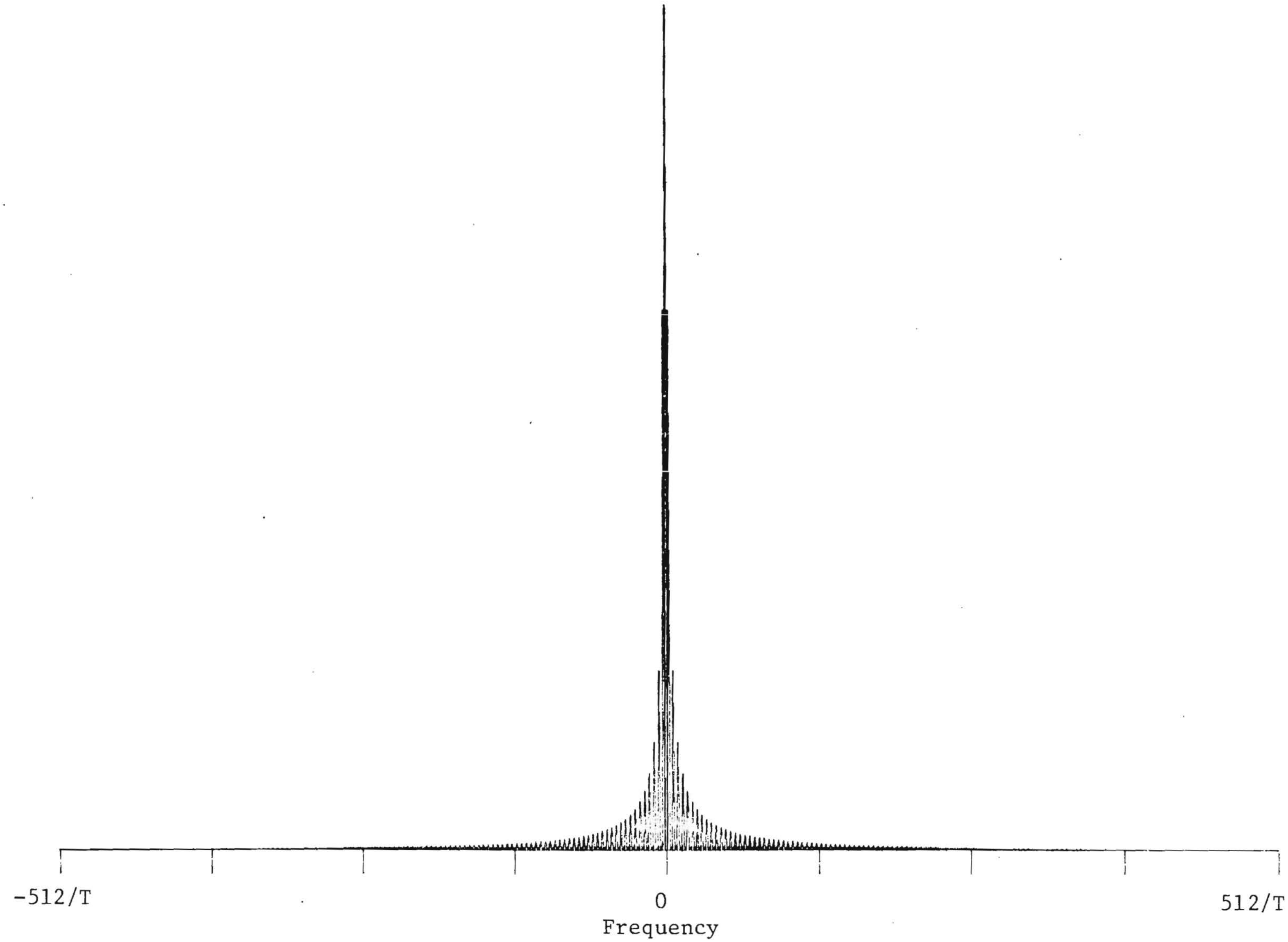

Figure 6-22. Frequency Spectrum of Object Function of Figure 6-21 on a Linear Plot.

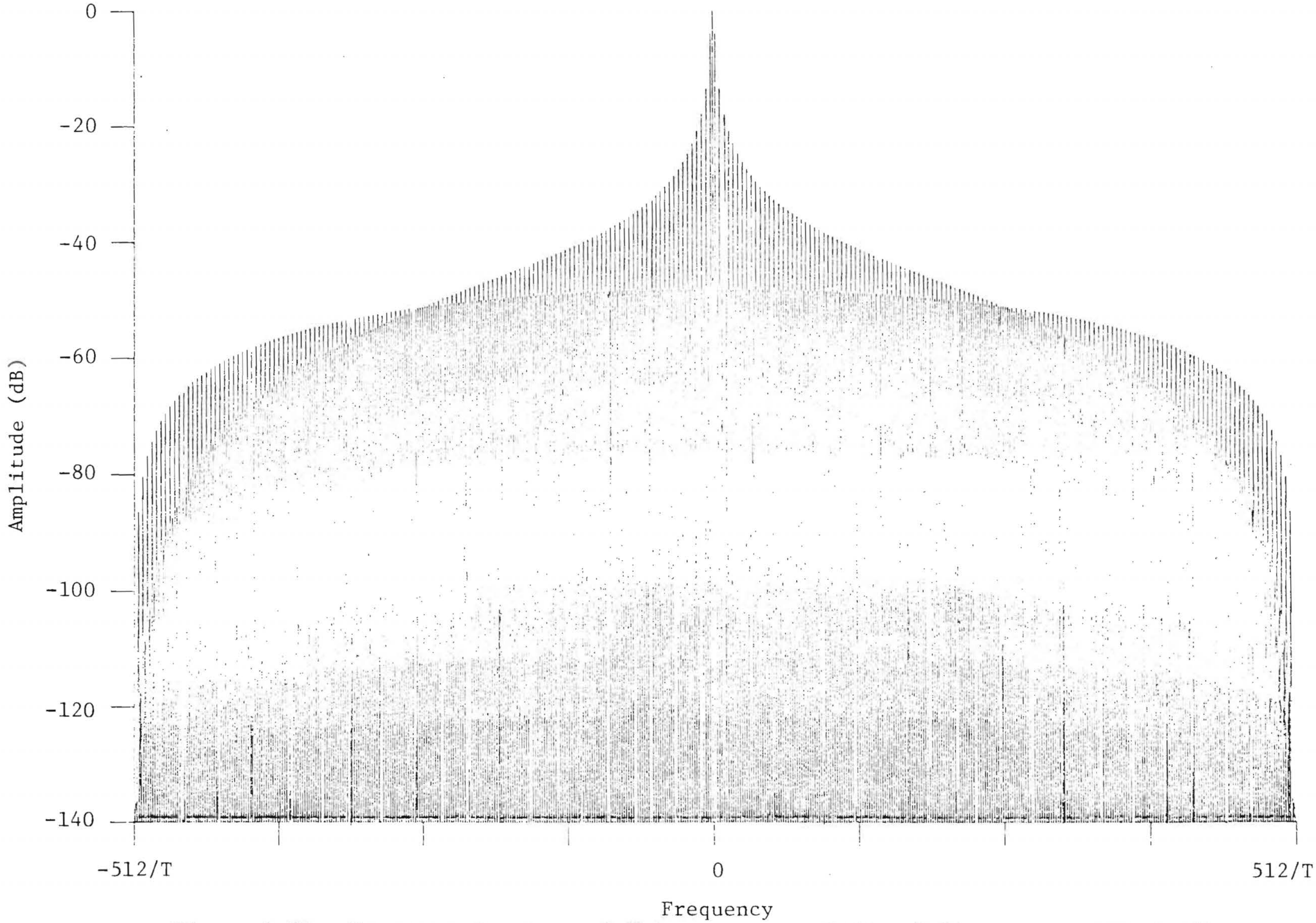

Figure 6-23. Frequency Spectrum of Object Fuction of Fig. 6-21 on a Logarithmic Plot.

logarithmic amplitude scale. Figure 6-24 displays the input function with a linear decay applied so that the initial portion of the waveform decays to 0.1 of its initial amplitude by the time that the end of the waveform occurs. Figures 6-25 and 6-26 are linear and log amplitude plots of the frequency spectrum of the input function shown in Figure 6-24. The effect of the window function in this case was to fill in the frequency spectrum between the discrete frequency components of the square wave, which for the ideal square wave occur at the fundamental frequency of the square wave and at all odd harmonic frequencies. The product of two input functions, represented as two time waveforms, transform to the convolution of the two individual frequency spectra. Mathematically

$$h(t)\ g(t) \leftrightarrow H(f) * G(f), \qquad (6\text{-}5)$$

where * denotes convolution. The square wave spectra containing only odd harmonics is convolved with the saw tooth function having both even and odd harmonics.

A clearer demonstration of this process is shown in Figures 6-27 through 6-32 which show the waveform and frequency spectra of a square wave with 16 cycles per sampling interval of the input signal. Decreasing the period of the input signal results in an increase in the spacing of the transform components. Figures 6-27 through 6-29 show the input signal without a window function applied and its linear and logarithmic transforms. Figures 6-30 through 6-32 show the same information for the same input signal to which a linear decay function has been applied over the interval for which the input function was sampled. These cases of idealized waveforms indicate that the effect of the window function is to fill in the frequencies between the transform components of the square wave while the transfer component amplitudes of the square wave are not affected.

A case consisting of an input signal which consists mostly of a square wave but which has beginning and ending periods which deviate slightly from the square wave period is shown in Figures 6-33 through 6-38. A window function decaying to an amplitude of 0.1 was applied to this signal. The unsymmetrical portion of the square wave produced spectral components not present with the symmetrical square wave.

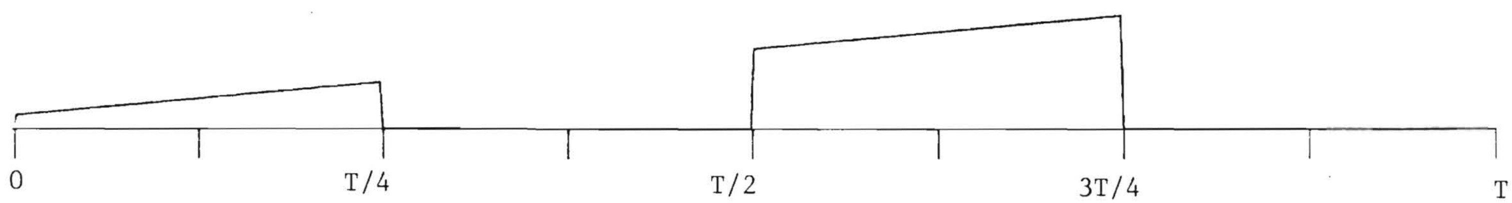

Figure 6-24. Object Function of Figure 6-21 Having a Linear Decay to 0.1 of its Original Amplitude Over a Time Interval T.

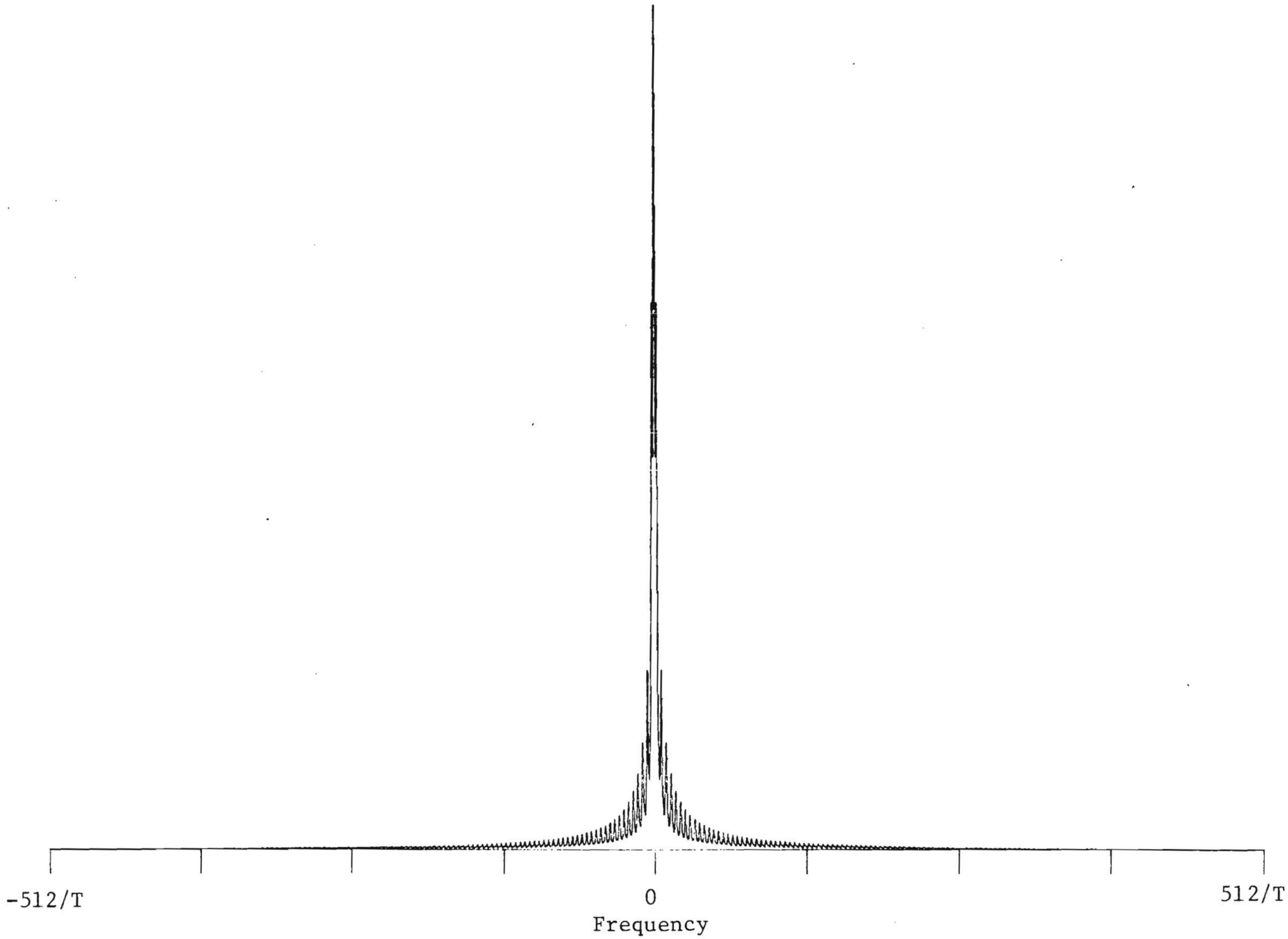

Figure 6-25. Frequency Spectrum of Object Function of Figure 6-24 on a Linear Plot.

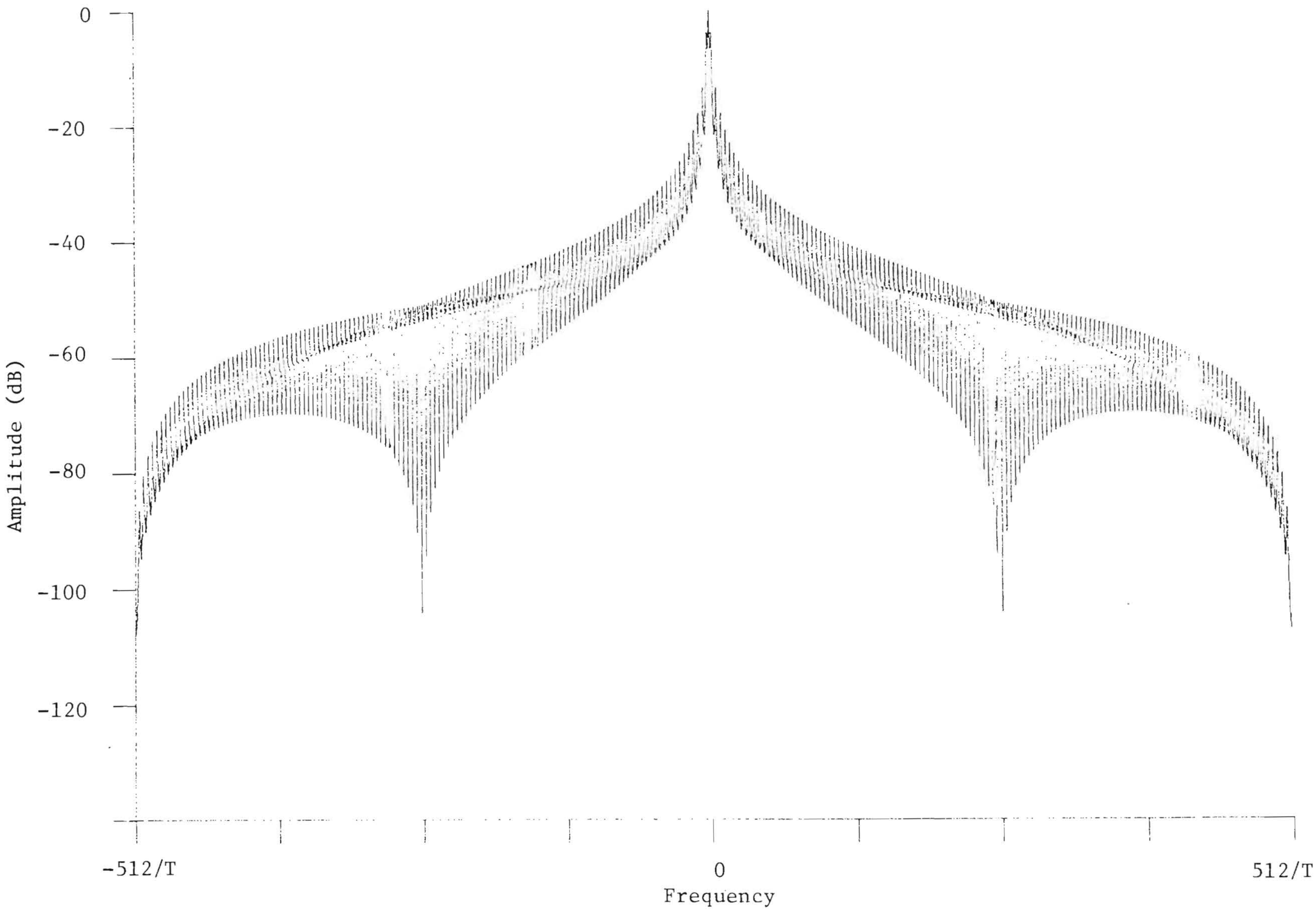

Figure 6-26. Frequency Spectrum of Object Function of Fig. 6-24 on a Logarithmic Plot.

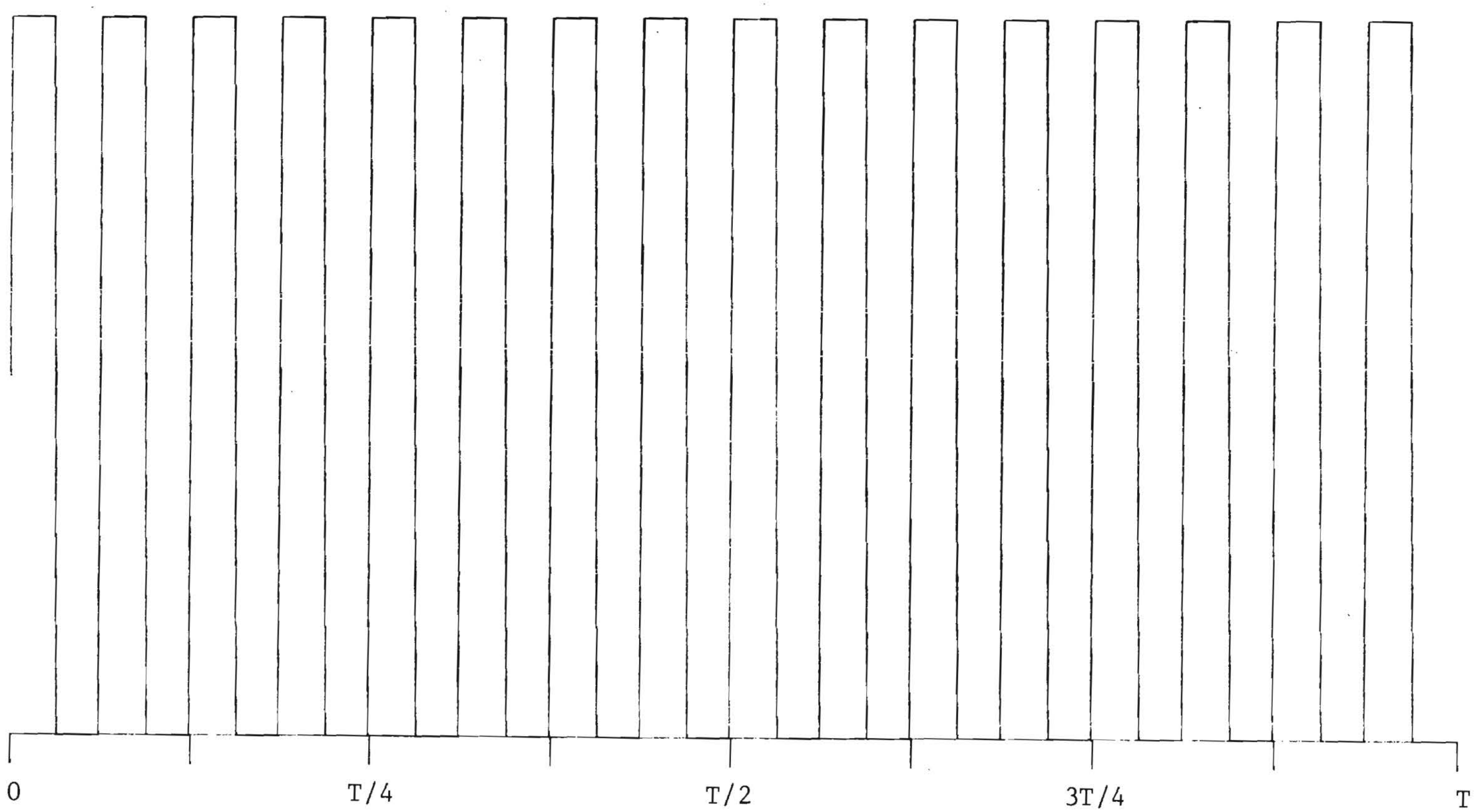

Figure 6-27. Input Object Function Consisting of a 16 Cycle Square Wave.

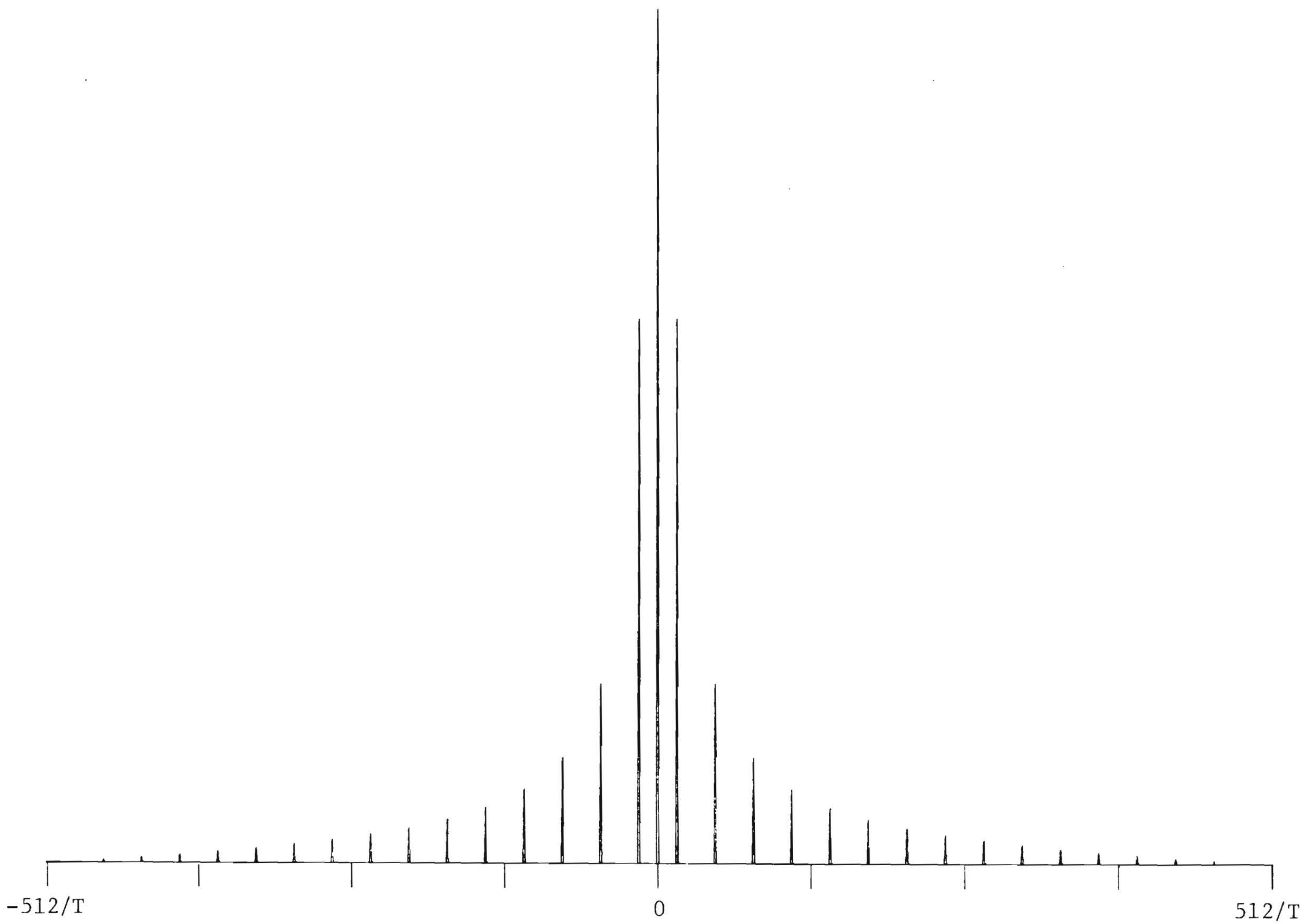

Figure 6-28. Frequency Spectrum of Object Function of Figure 6-27 on a Linear Plot.

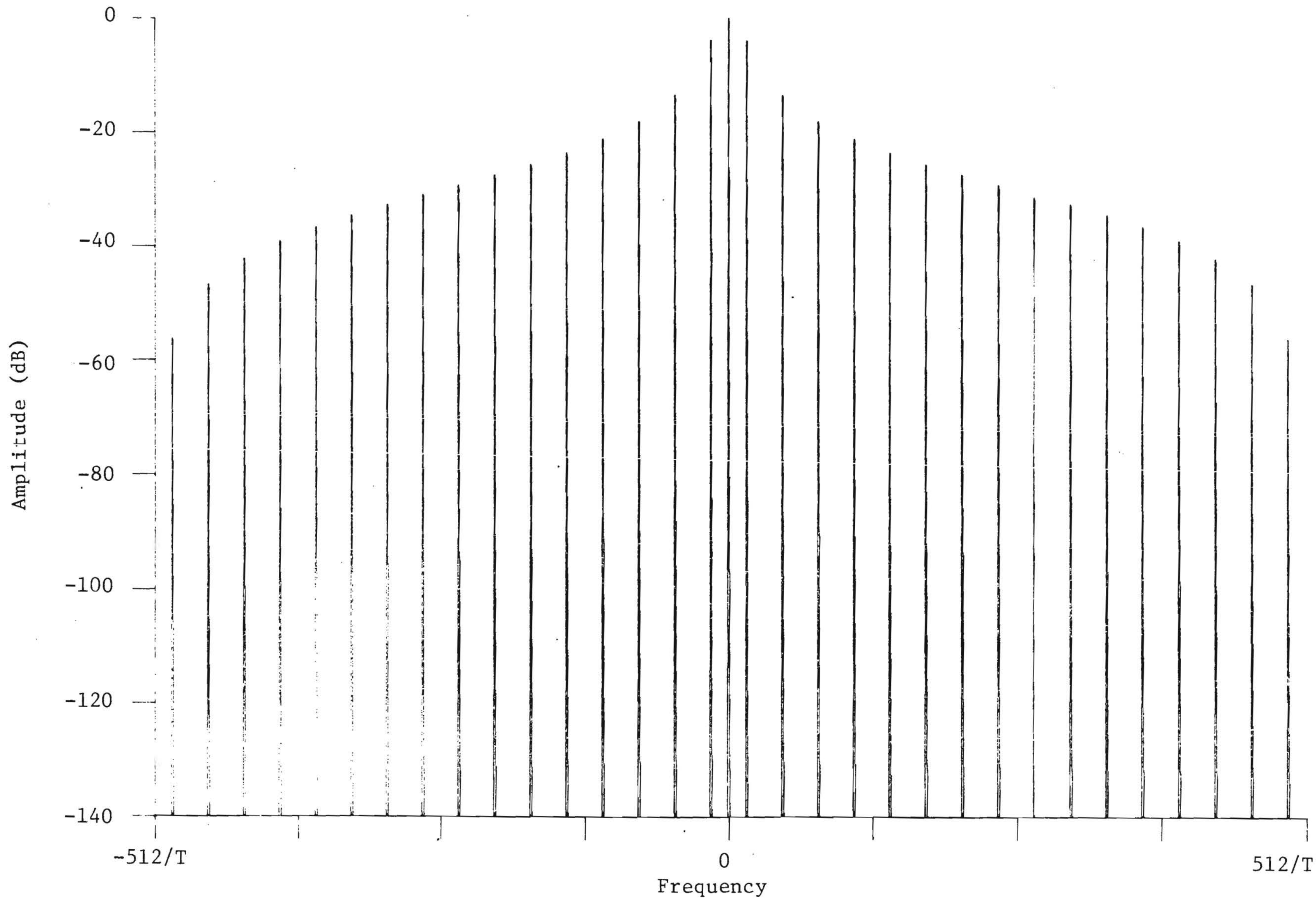

Figure 6-29. Frequency Spectrum of Object Function of Figure 6-27 on a Logarithmic Plot.

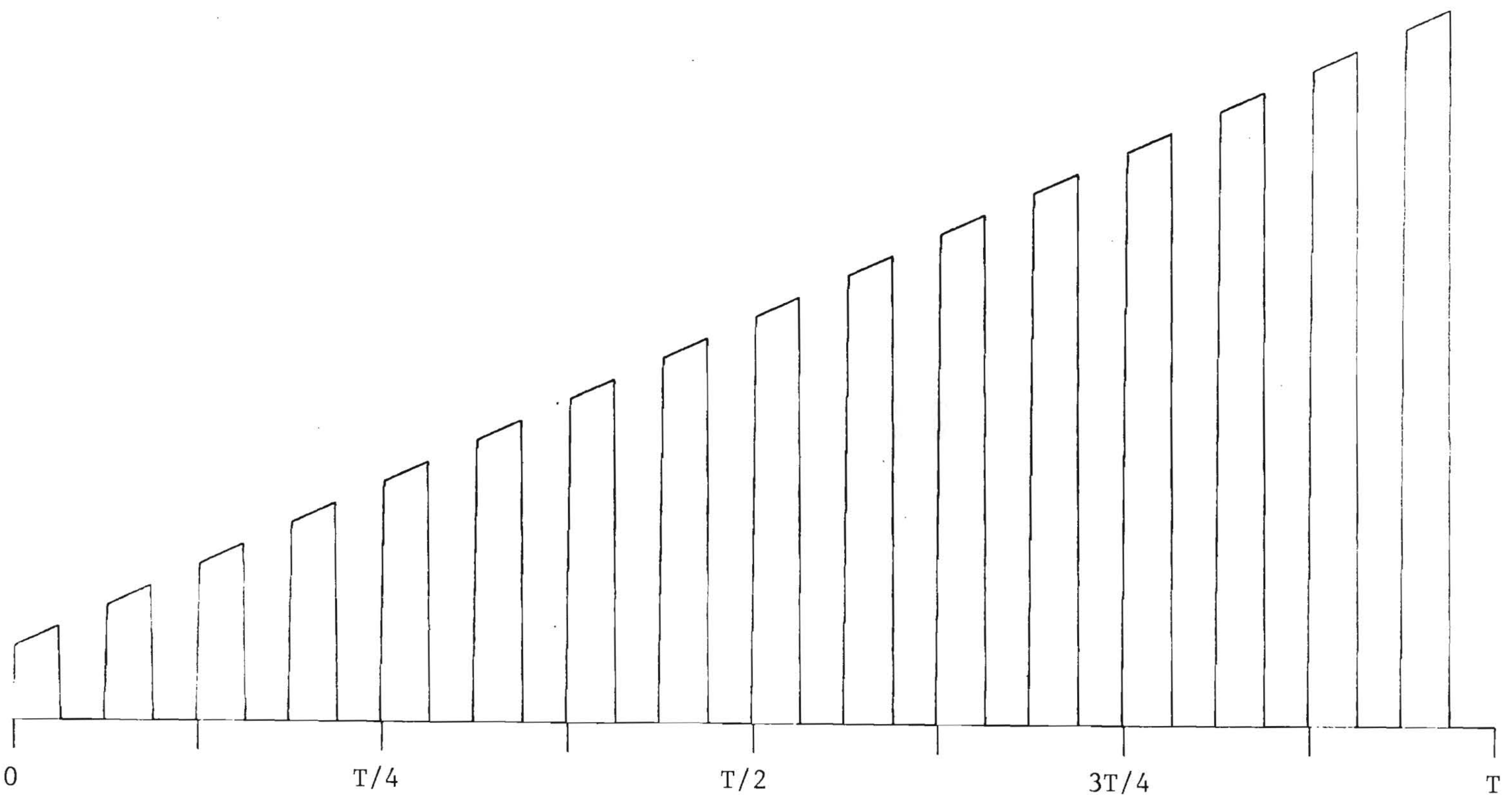

Figure 6-30. Input Object Function of Figure 6-27 Having a Linear Decay to 0.1 of its Original Amplitude Over a Time interval T.

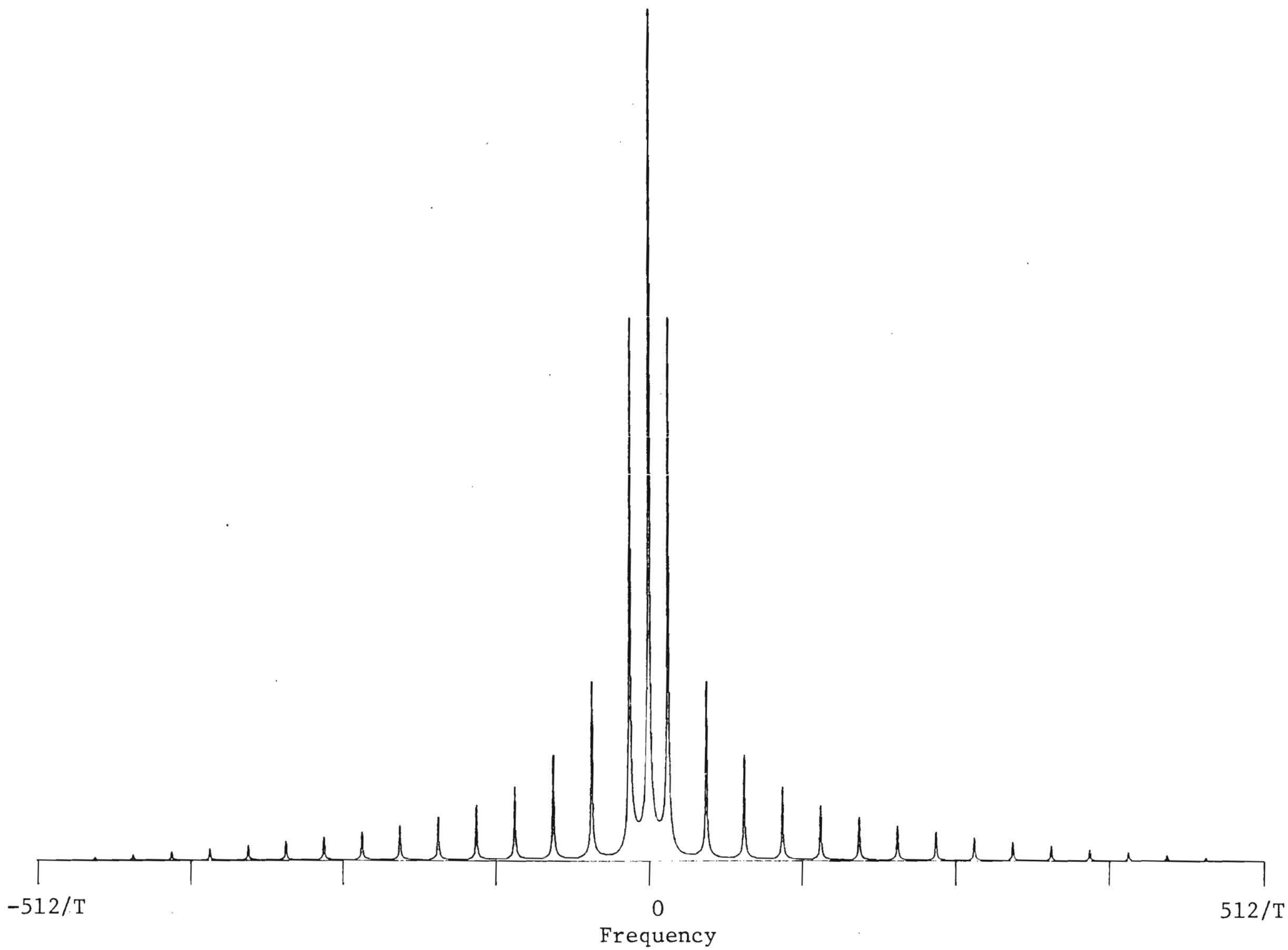

Figure 6-31. Frequency Spectrum of Object Function of Figure 6-30 on a Linear Plot.

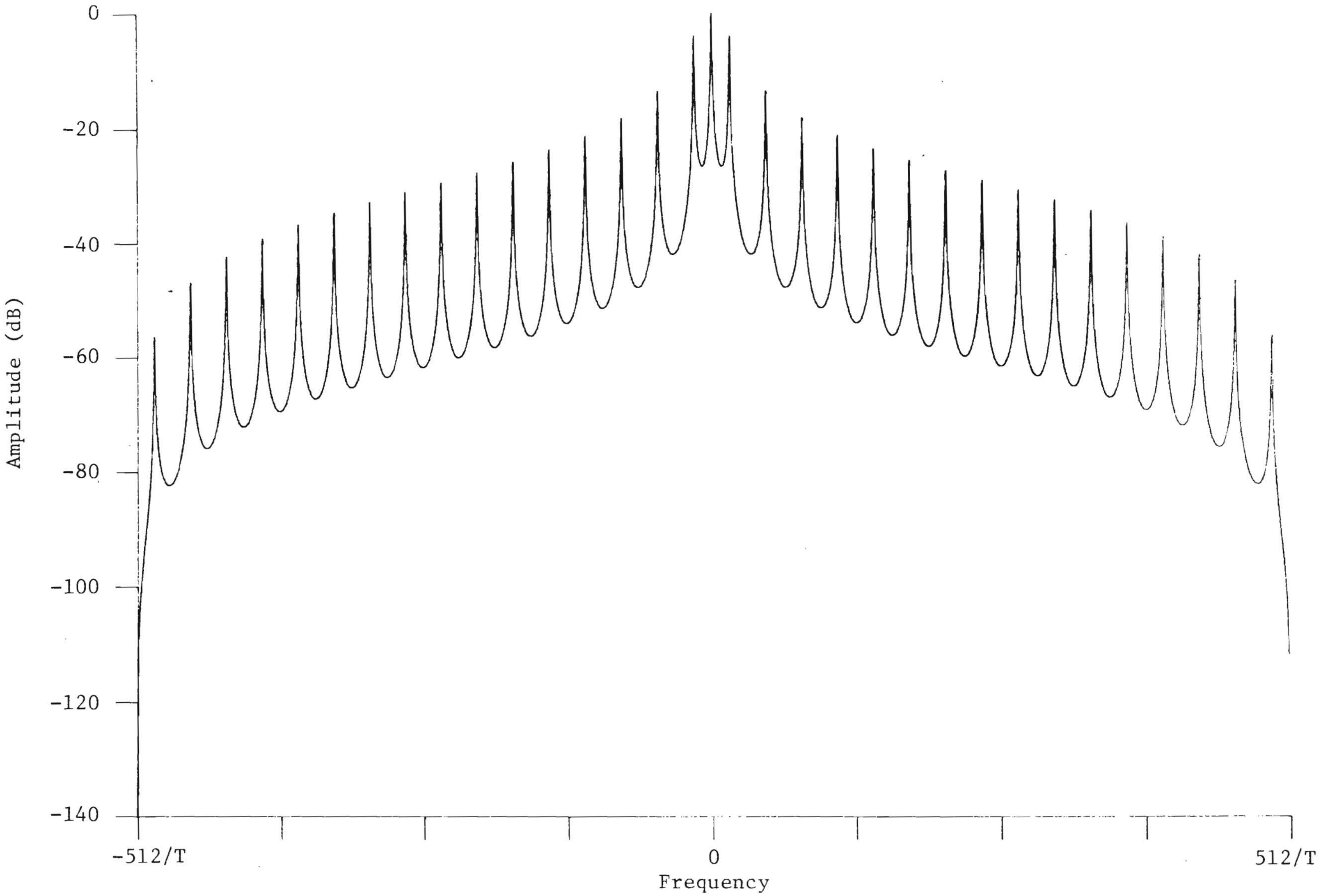

Figure 6-32. Frequency Spectrum of the Object Function of Figure 6-30 on a Logarithmic Plot.

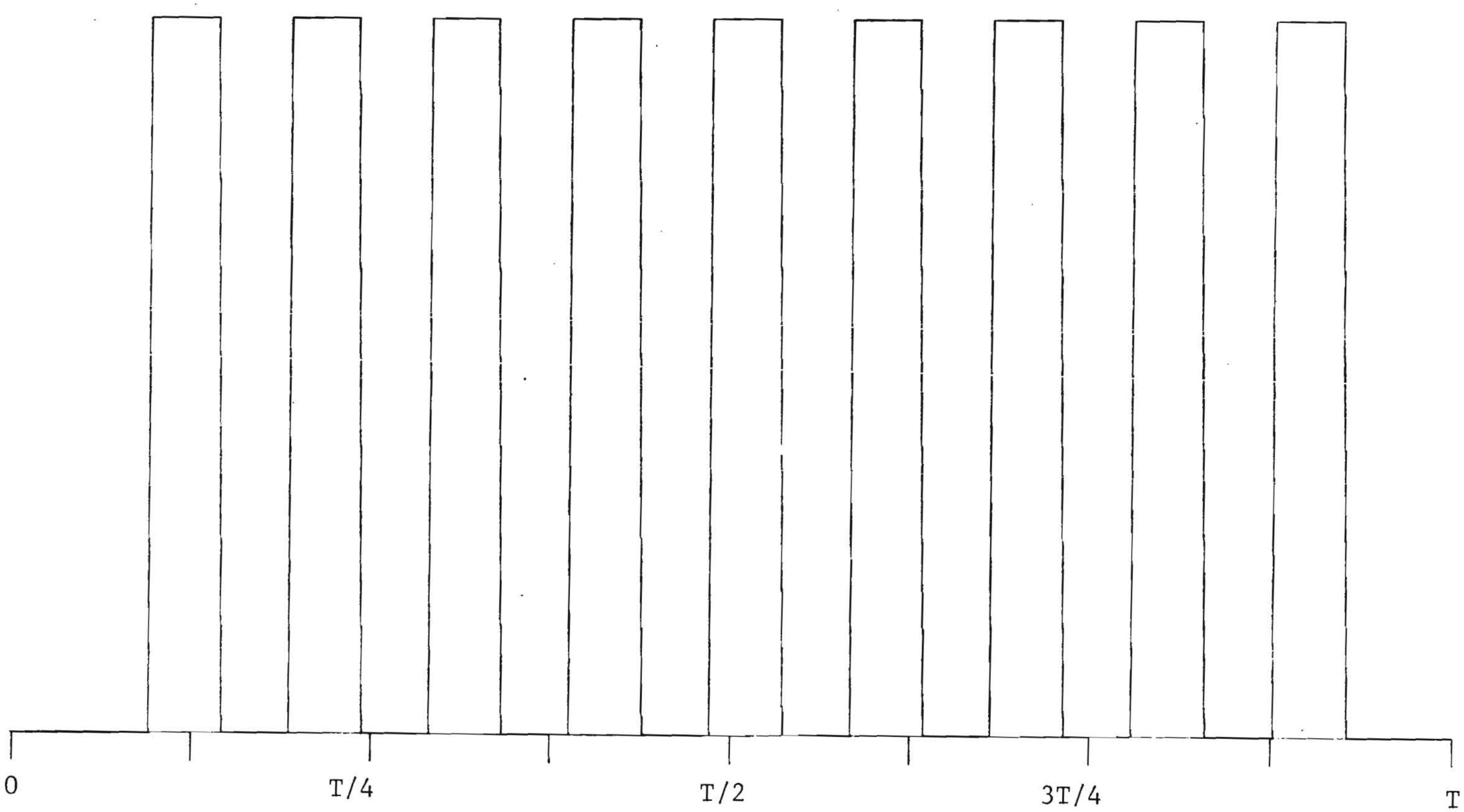

Figure 6-33. Input Object Function Consisting of a Square Wave Which is Not Periodic Over the Period T.

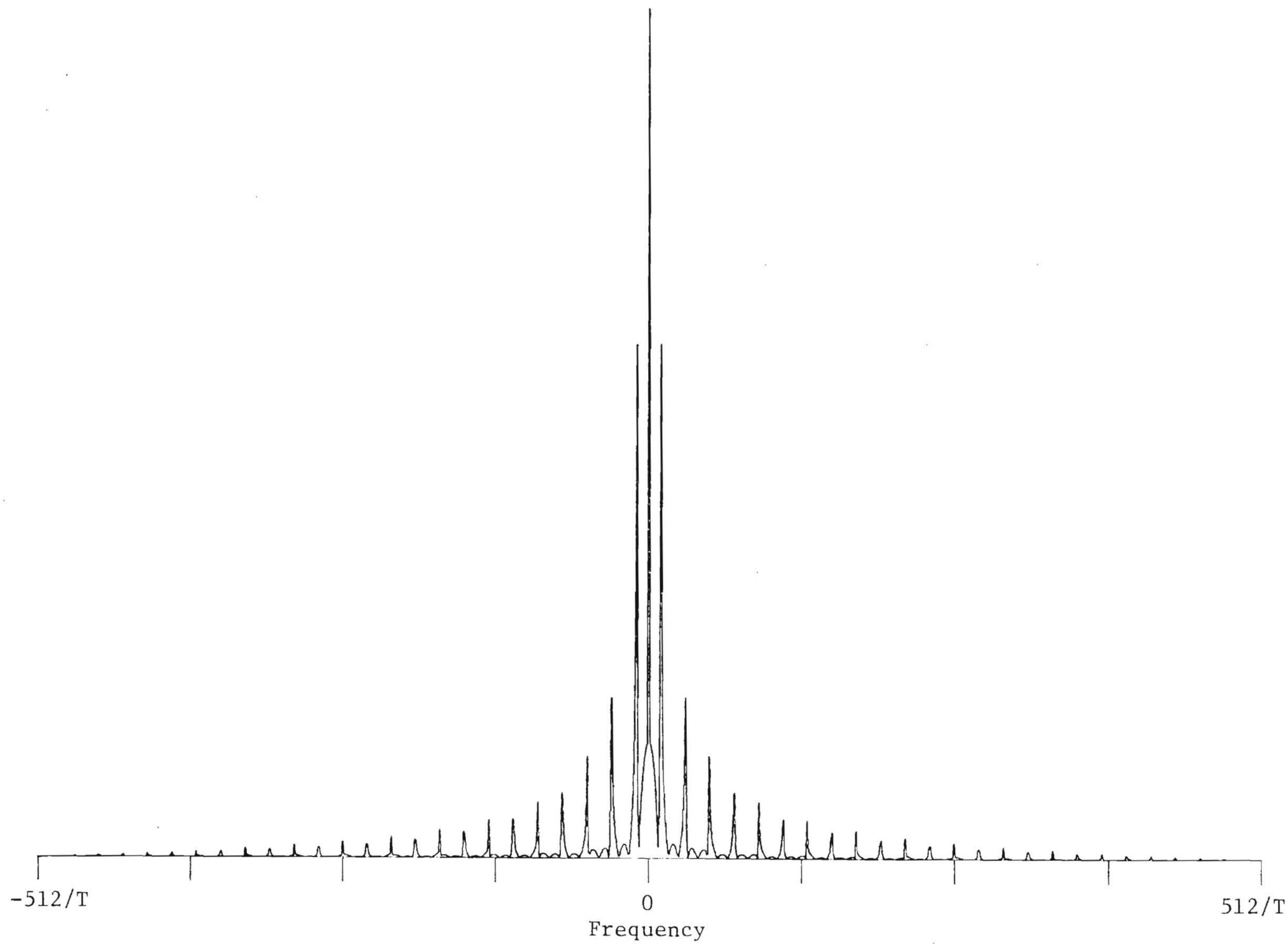

Figure 6-34. Frequency Spectrum of Object Function of Fig. 6-33 on a Linear Plot.

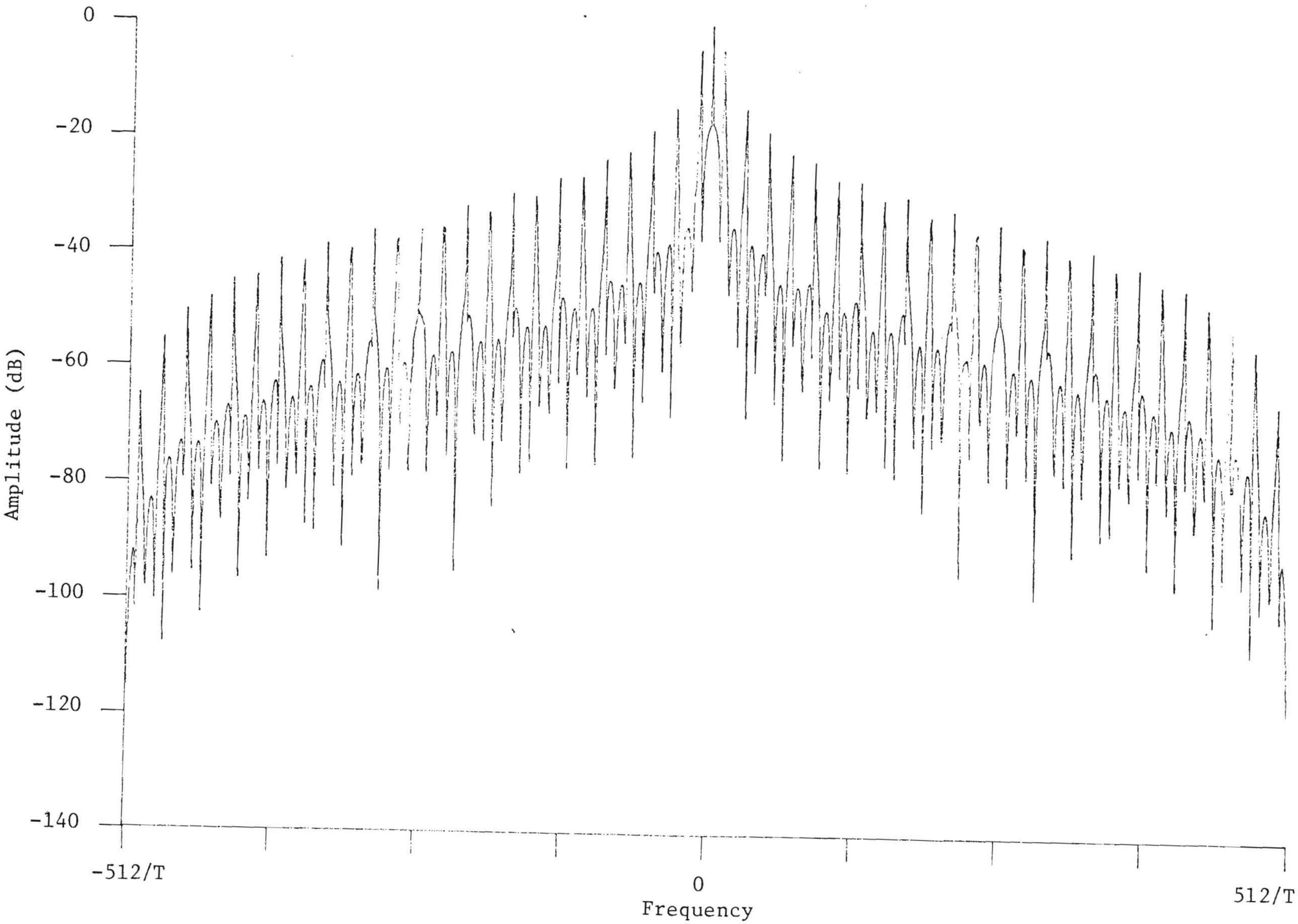

Figure 6-35. Frequency Spectrum of Object Function of Figure 6-33 on a Logarithmic Plot.

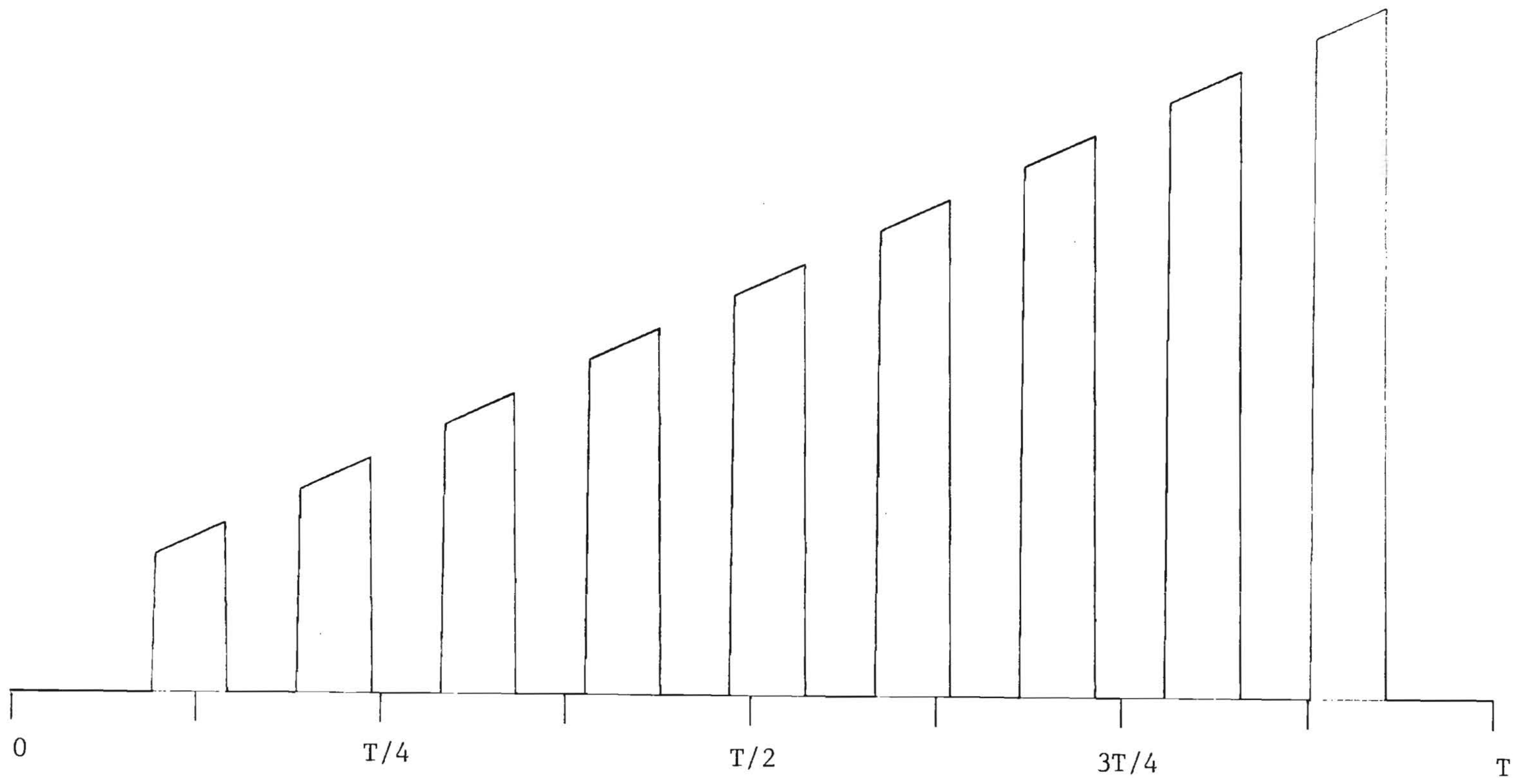

Figure 6-36. Input Object Function of Figure 6-33 Having a Linear Decay to 0.1 of its Original Amplitude Over a Time Interval T.

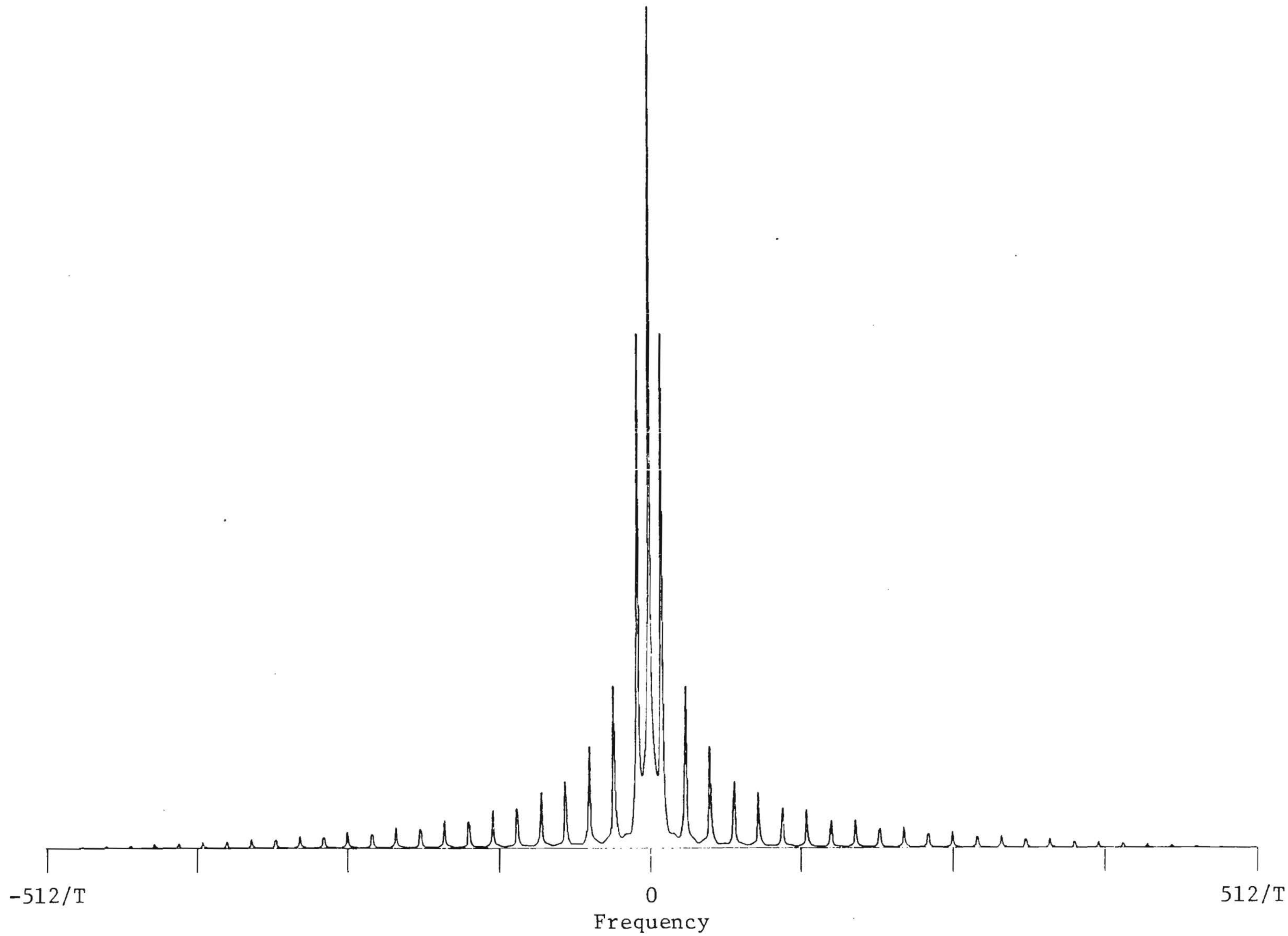

Figure 6-37. Frequency Spectrum of Object Function of Figure 6-36 on a Linear Plot.

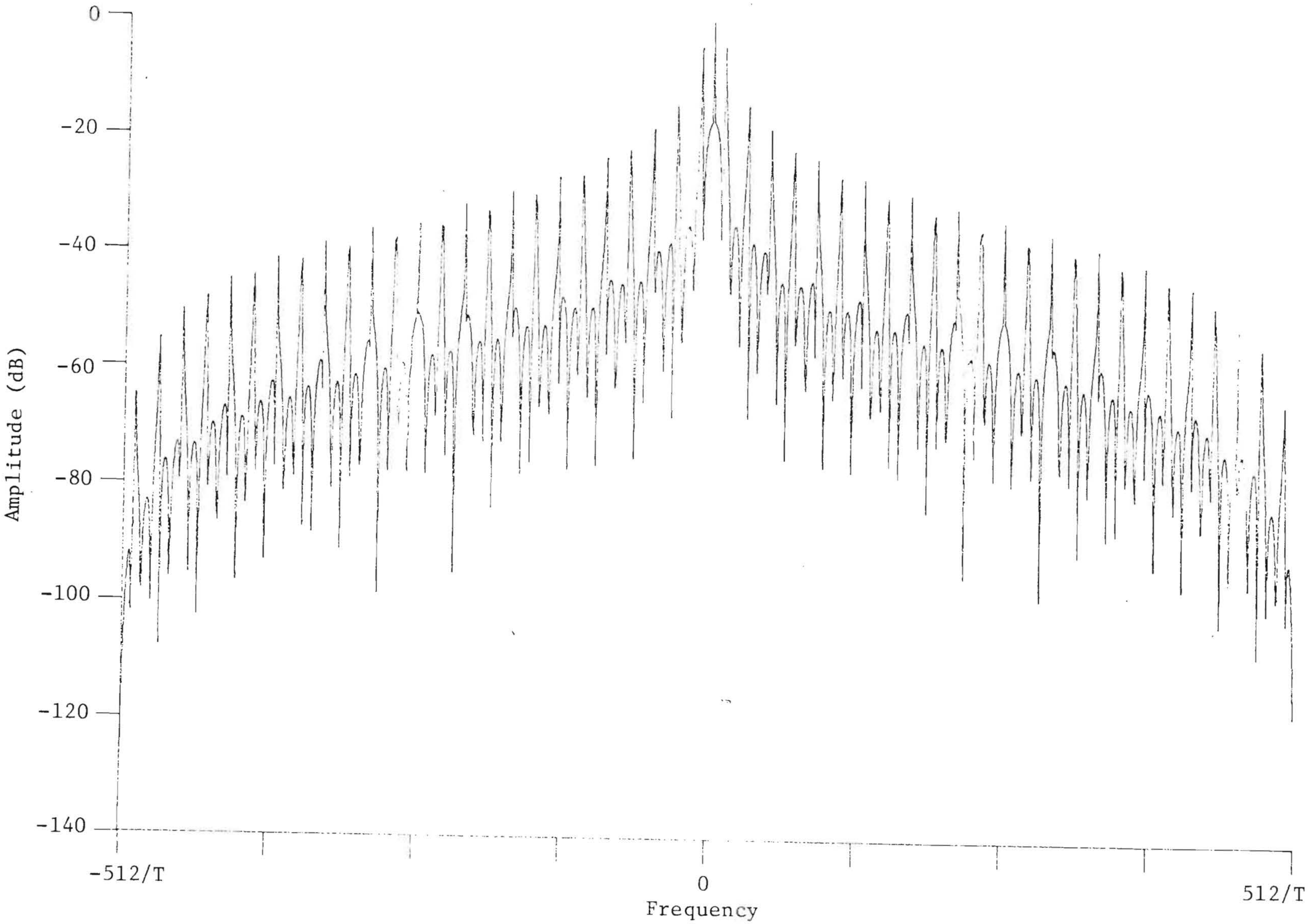

Figure 6-38. Frequency Spectrum of the Object Function of Figure 6-36 on a Logarithmic Plot.

A more general case was selected where the input waveform was an arbitrary function of amplitude over the sampling interval. This input waveform is shown in Figure 6-39 and its transform on linear and log scales is shown in Figures 6-40 and 6-41 respectfully. Figures 6-42 through 6-44 show the input waveform and the transforms for a decay function for which the initial amplitude decays to 0.1 of the initial value during the sampling intervals. Figures 6-45 through 6-47 show the same information for a decay function for which the initial amplitude decays to zero during the sampling interval. Observation of the spectra shows for this case the variation of the frequency domain components is of the order of 20 dB between the case of no decay and for the case of decay to zero during the sampling interval.

Time did not permit further investigation of decay functions other than the simple ones discussed. The computer programs have been constructed to allow investigation of other more complex decay functions. The simulations thus far have concerned only single dimension functions and their transforms. The capability is available for the consideration of two-dimensional functions (within the limits of machine storage capabilities and available time) and for consideration of more complex decay functions and image generation formats such as interlaced television formats.

The conclusion can be reached that the effects of the window functions cause a change in the transform spectra of input images, a conclusion which is expected. What is a little surprising, with the limited data available, is that the spectral change is not greater than it is. The largest changes were in the rather complicated spectra of Figures 6-41 and 6-47 and observed in the low frequency components, while the general shape of the frequency spectra remained essentially the same.

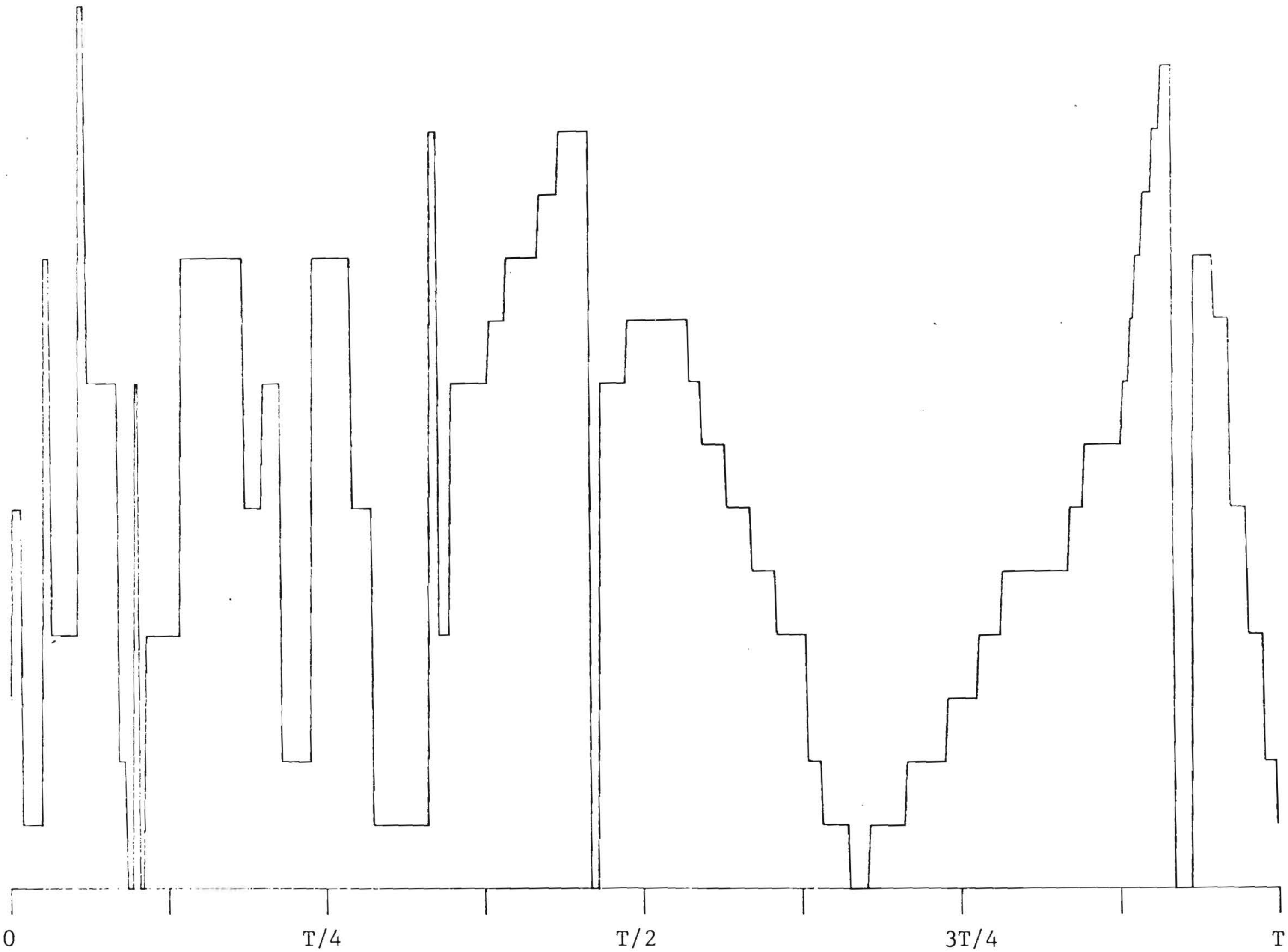

Figure 6-39. Input Object Function Simulating an Arbitrary Amplitude Function over the Sampling Interval.

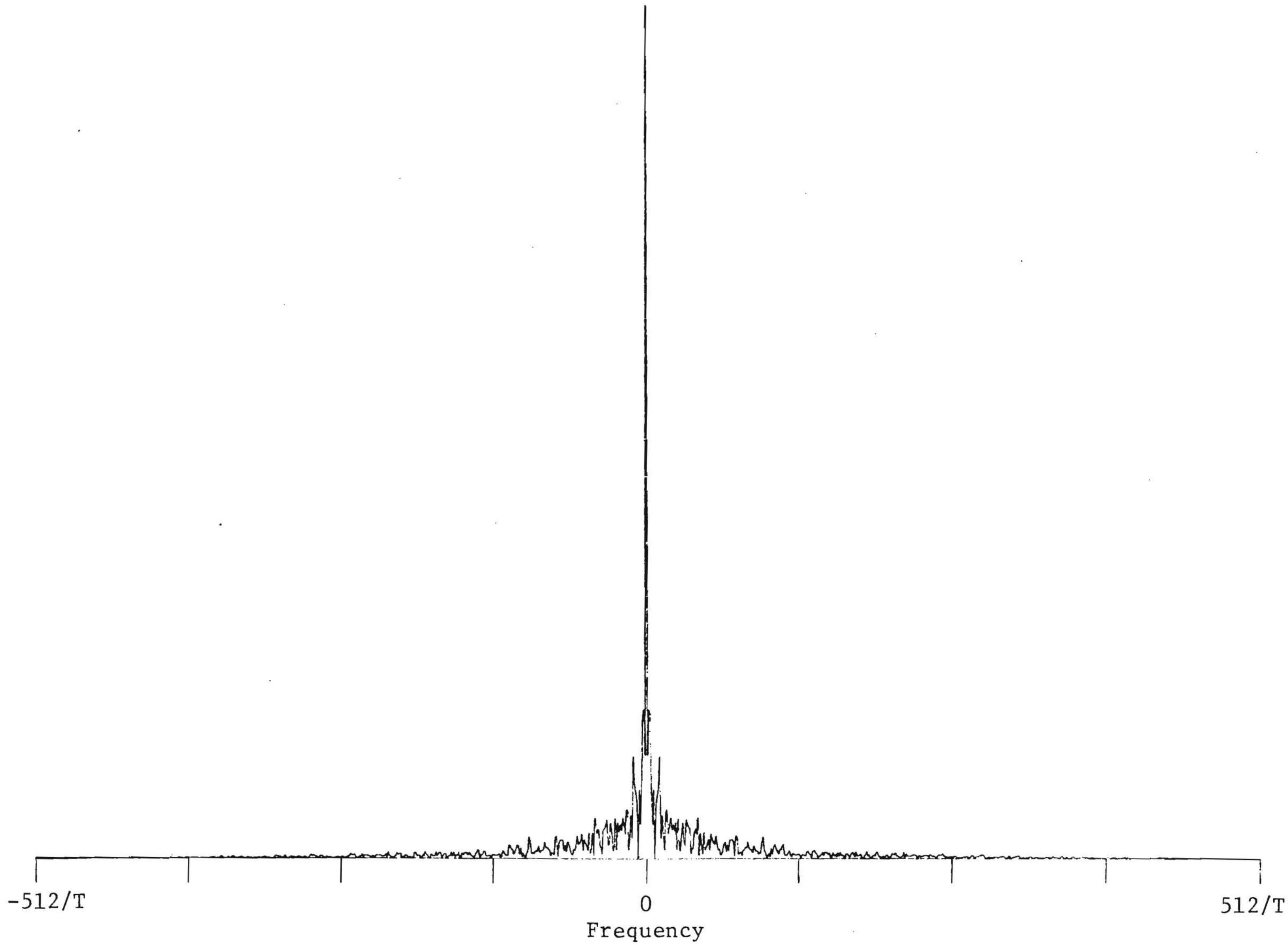

Figure 6-40. Frequency Spectrum of Object Function of Figure 6-39 on a Linear Plot.

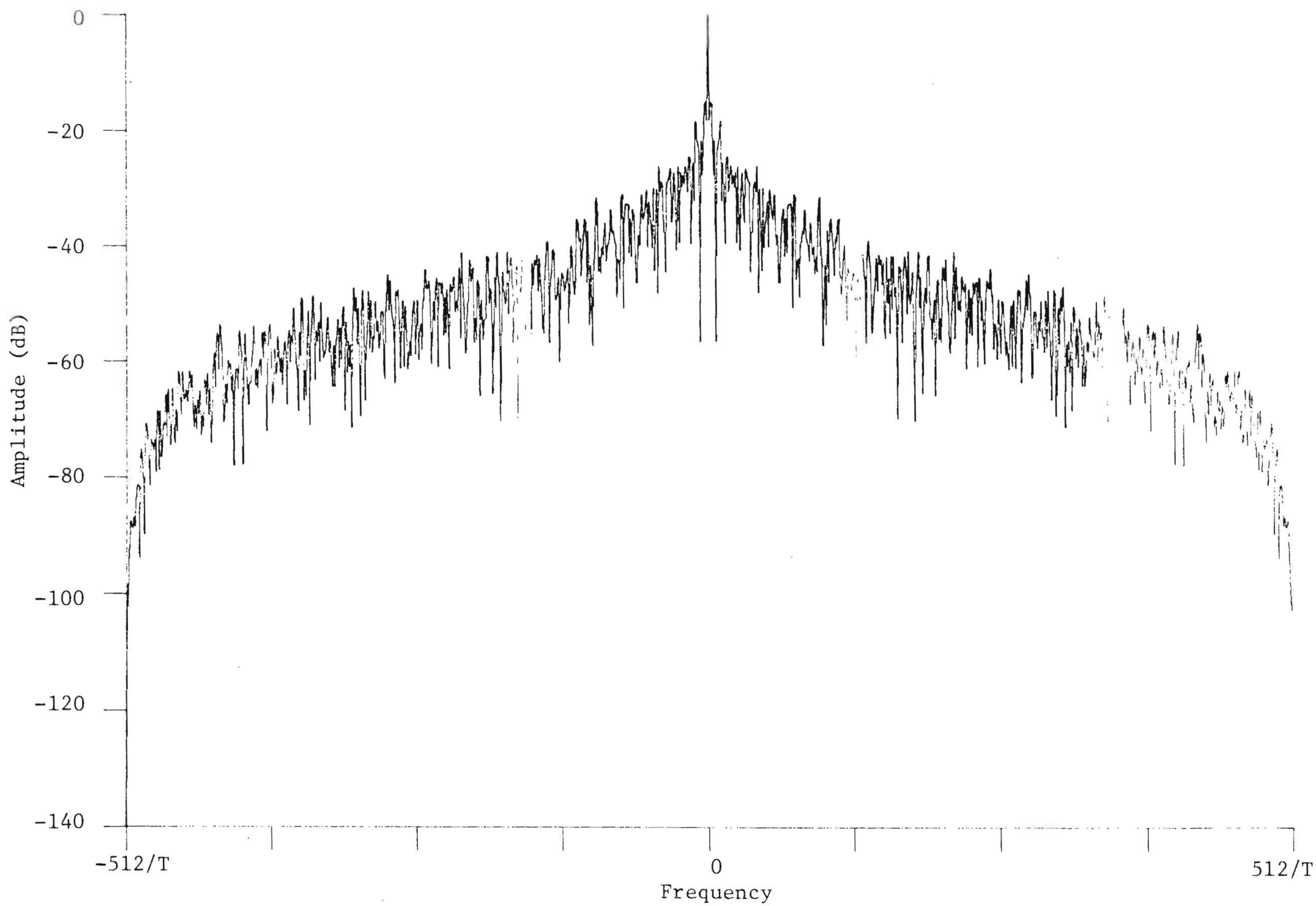

Figure 6-41. Frequency Spectrum of Object Function of Figure 6-39 on a Logarithmic Plot.

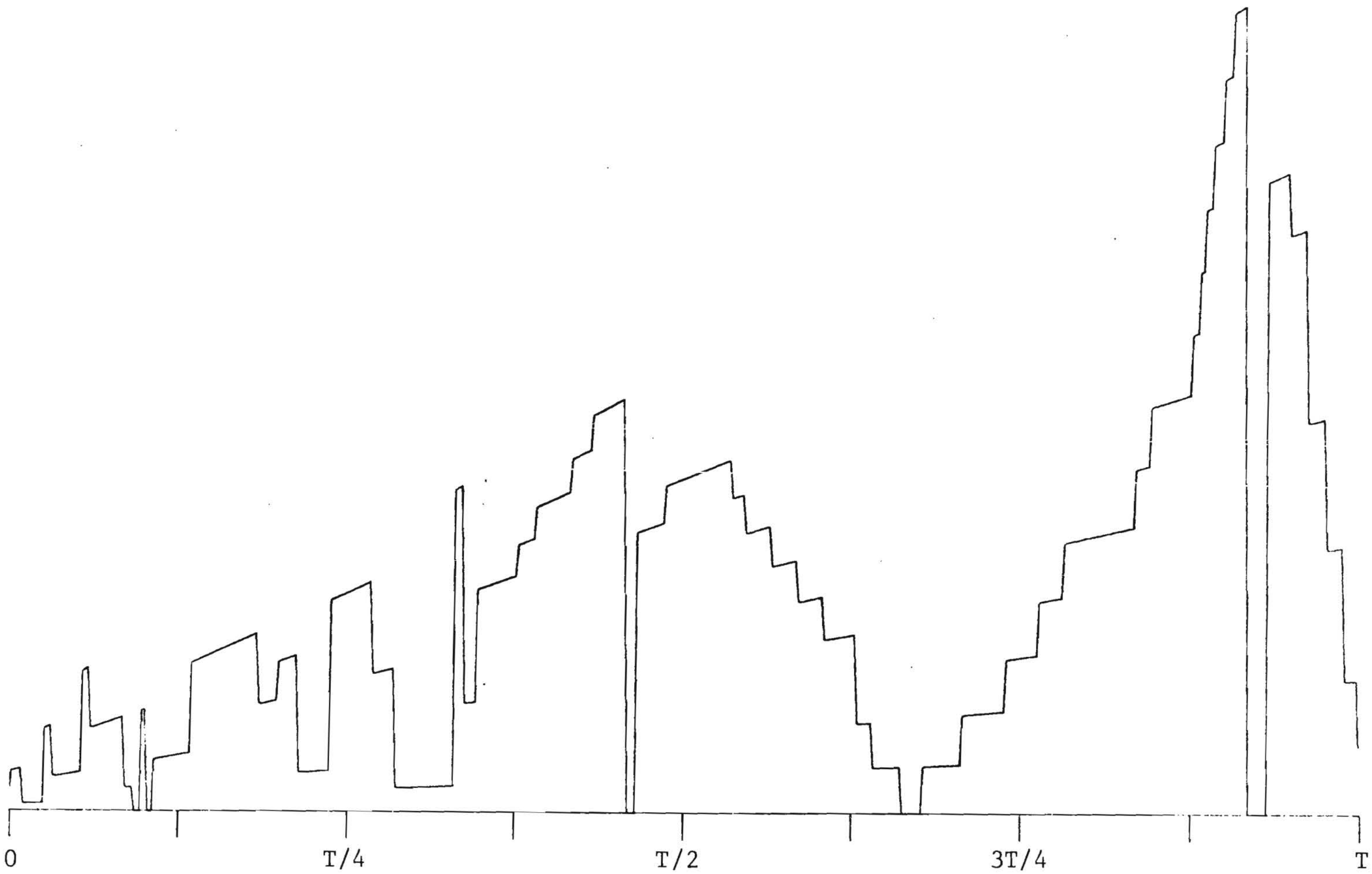

Figure 6-42. Object Function of Figure 6-39 Having a Linear Decay to 0.1 of its Original Amplitude Over a Time Interval T.

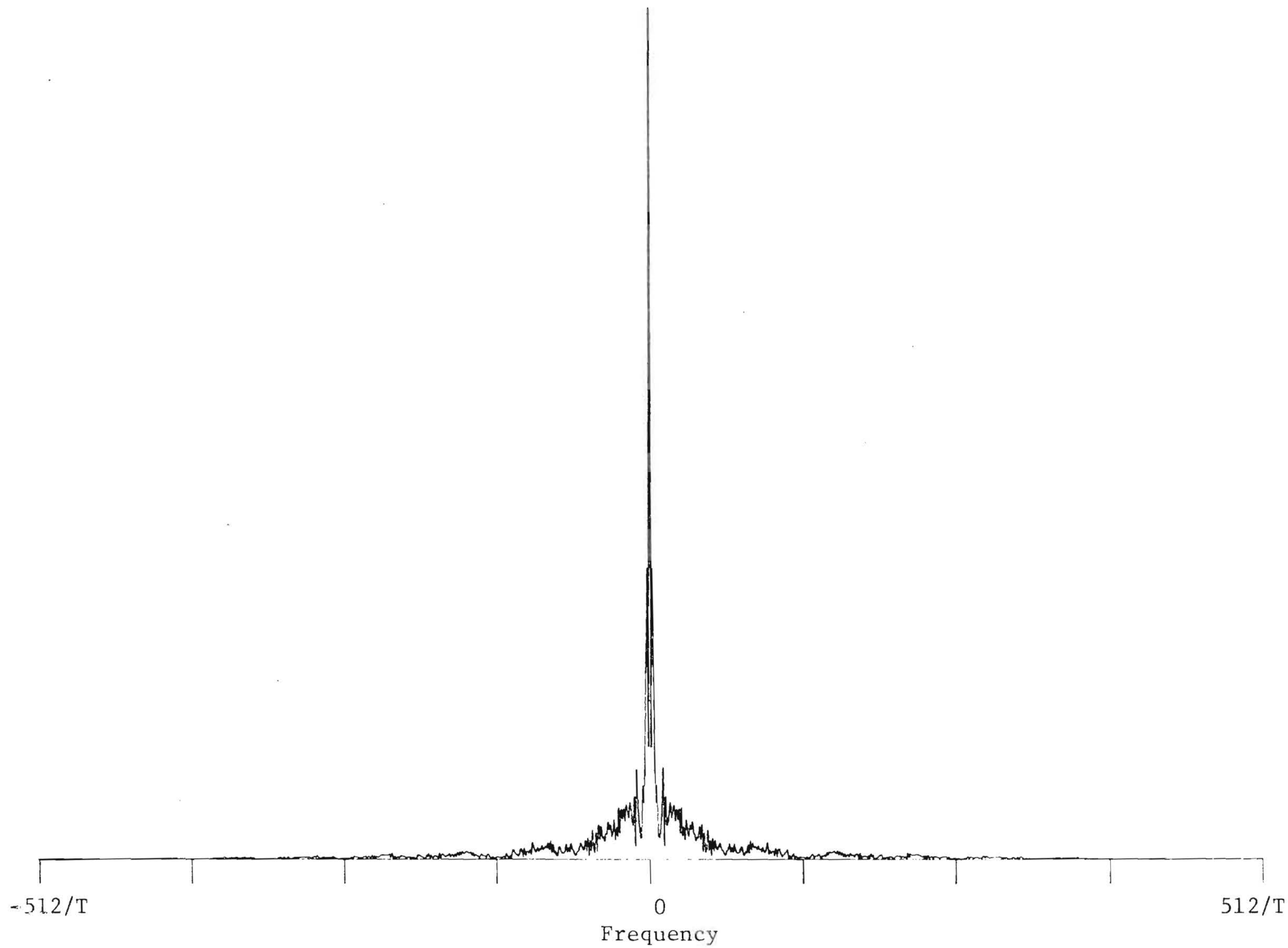

Figure 6-43. Frequency Spectrum at Object Function of Figure 6-42 on a Linear Plot.

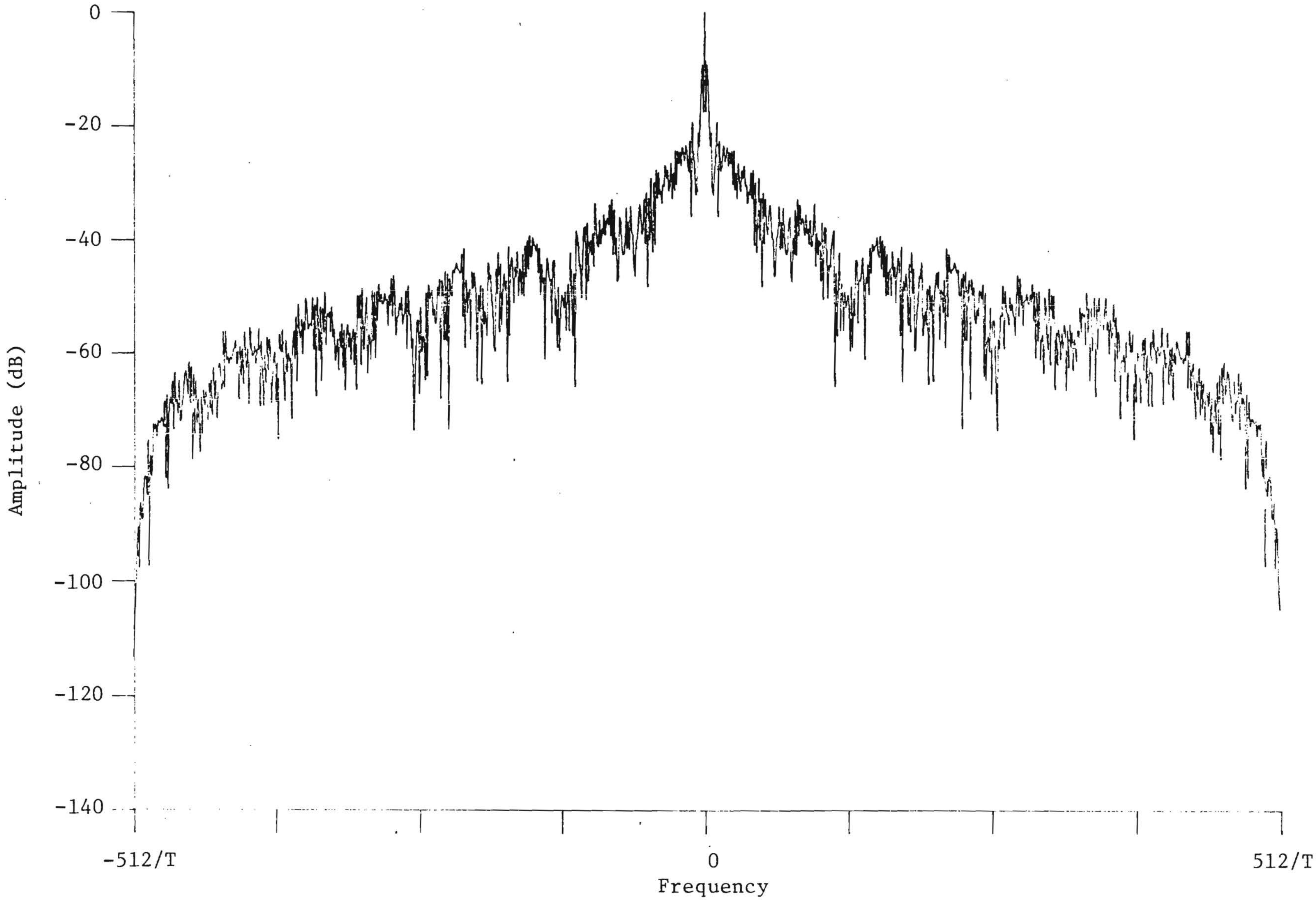

Figure 6-44. Frequency Spectrum of Object Function of Figure 6-42 on a Logarithmic Plot.

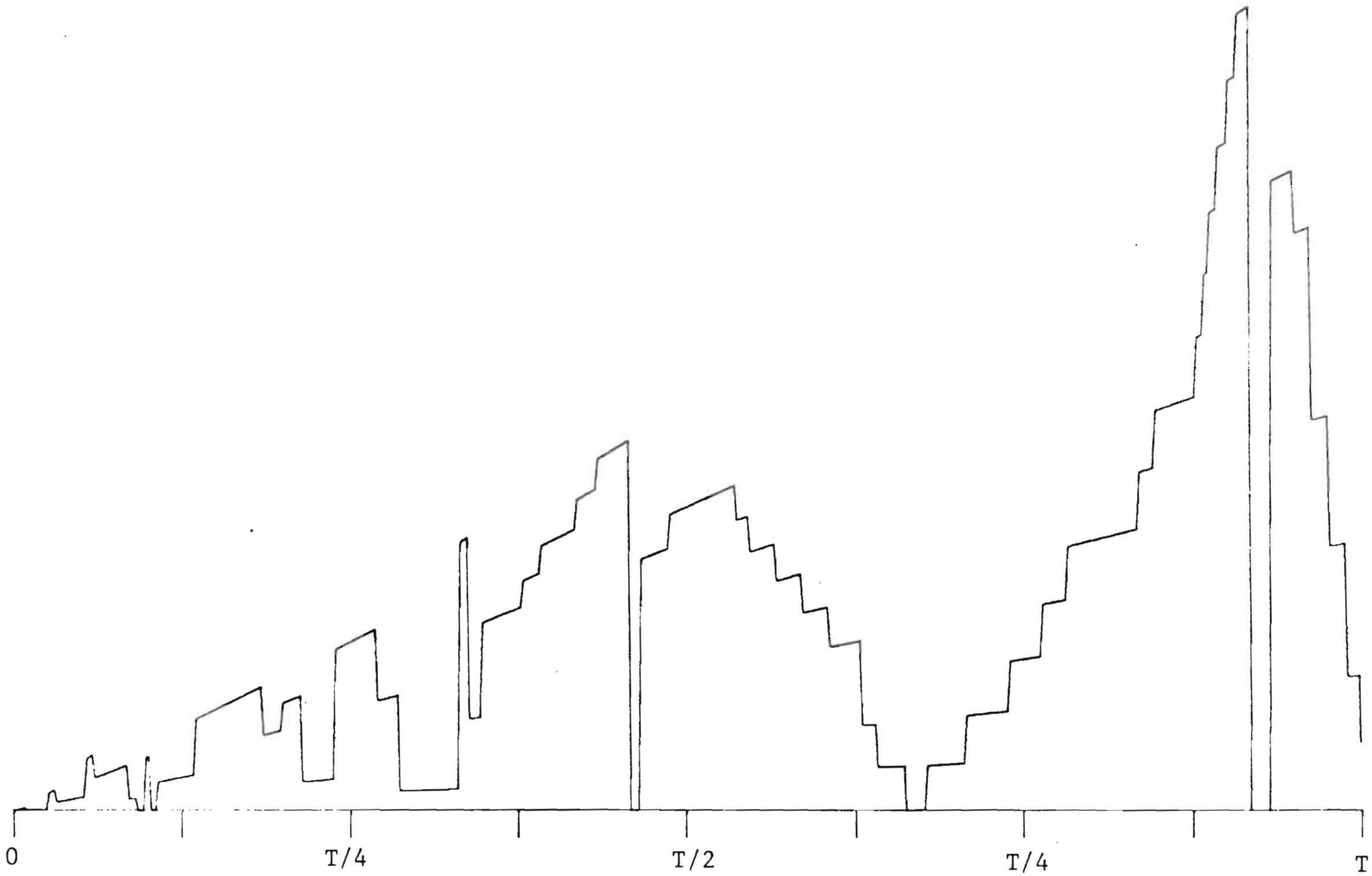

Figure 6-45. Object Function of Figure 6-39 Having a Linear Decay to 0.0 of its Original Amplitude Over a Time Interval T.

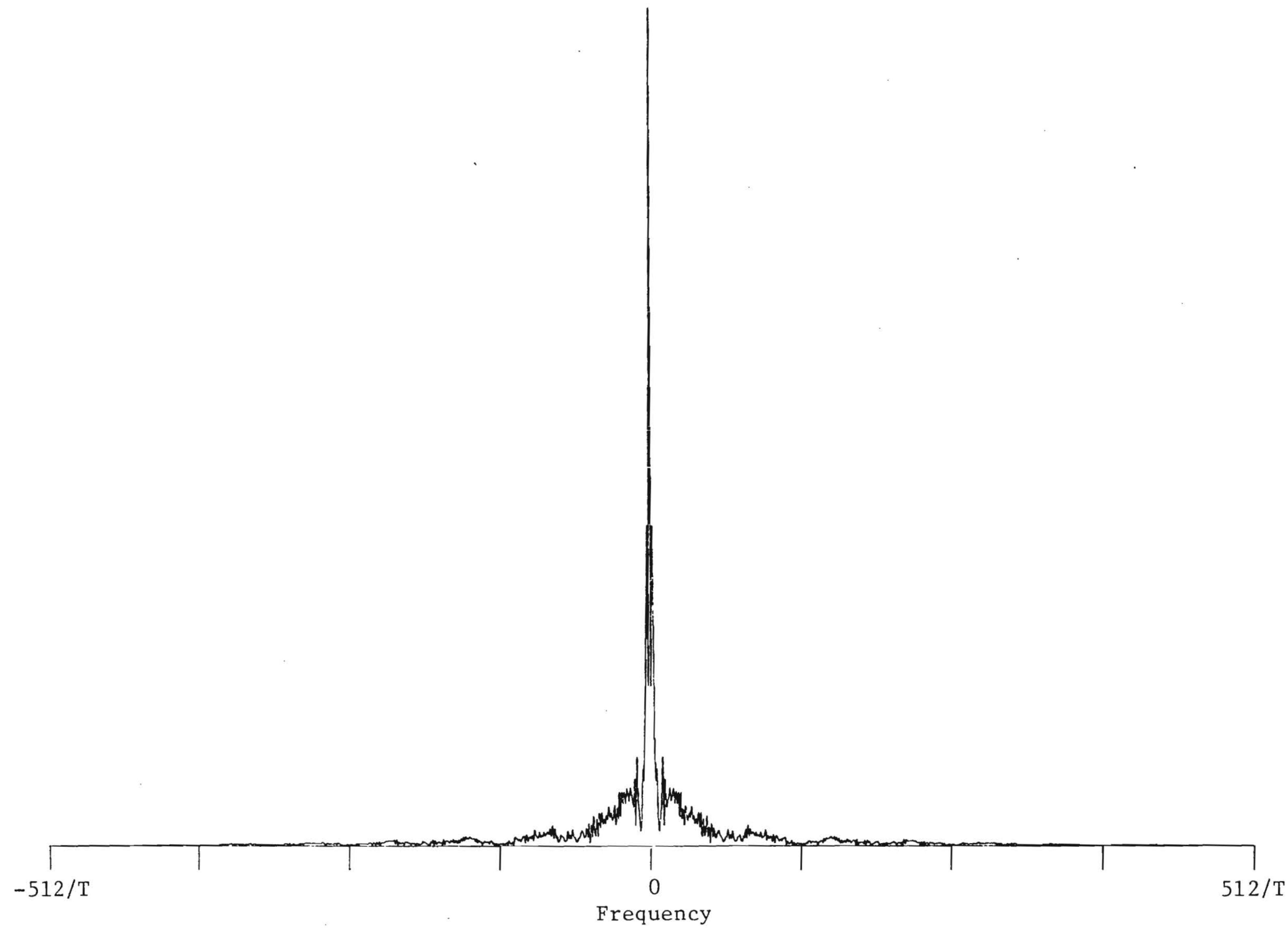

Figure 6-46. Frequency Spectrum of Object Function of Figure 6-45 on a Linear Plot.

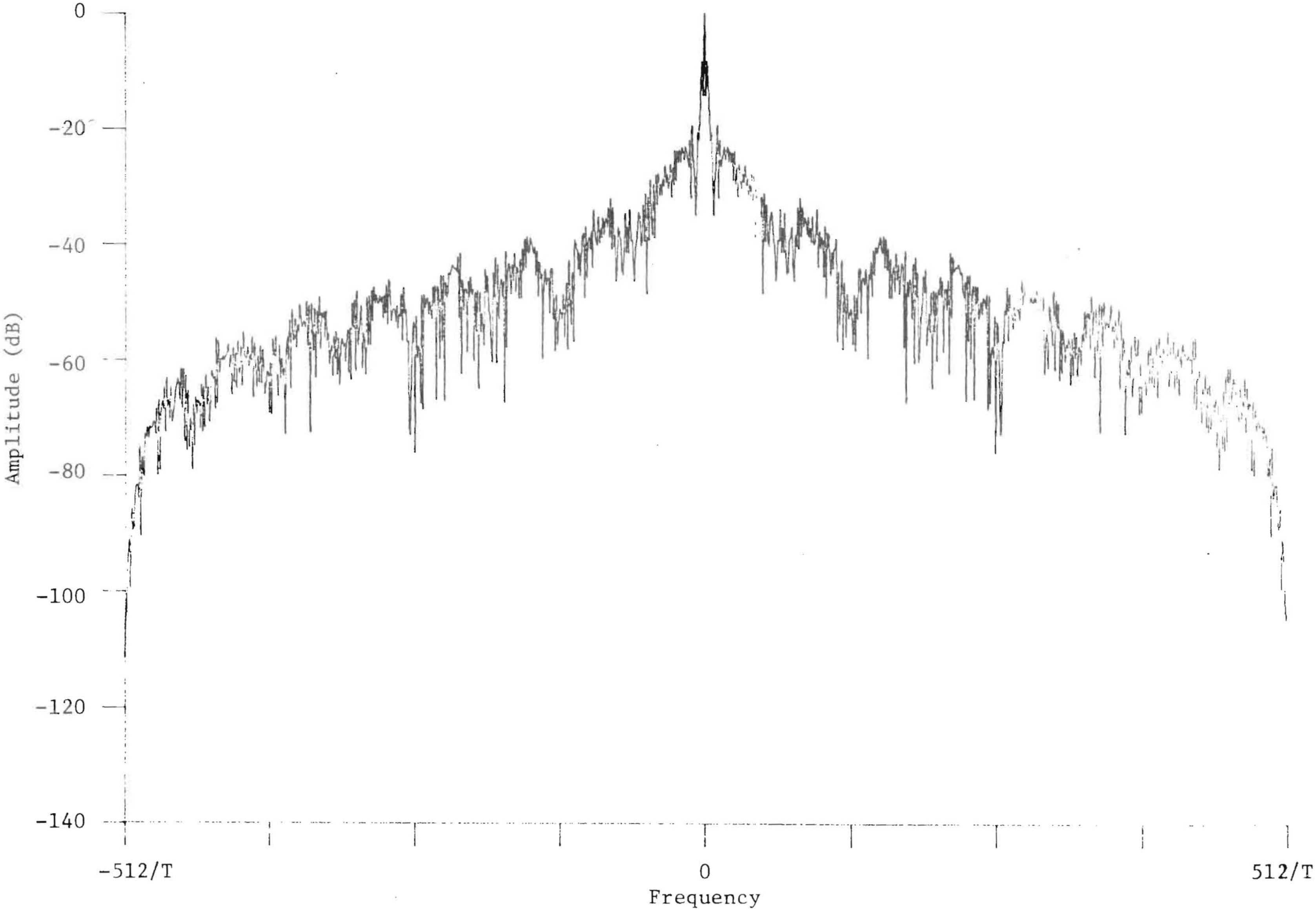

Figure 6-47. Frequency Spectrum of Object Function of Figure 6-45 on a Logarithmic Plot.

VII CONCLUSIONS AND RECOMMENDATIONS

This investigation has been carried out to determine the feasibility of an optical processor for on-board spacecraft operation. The investigation revealed that although real time optical processing is much nearer a reality than it was several years ago, there are still components critical to real time operation which need further developing and refinement. Among these critical components are the incoherent-to-coherent optical input devices for the object and filter planes, and the high resolution detector arrays for the output plane. Much of this effort has been directed toward an investigation of the impact of the operating characteristics of these devices on system performance, since these are, at present, the critical components of a real time optical processor.

The final success of a real time optical processor will depend in large part on the performance of the image input devices, which will be employed in both the input plane and the frequency domain filter plane. Photographic transparencies have traditionally been used for these functions; however, because of processing time delays, photographic film can hardly be classed as a real time input medium. While devices to provide the function of image inputting and filter function insertion in the transform plane display some similar characteristics, the demands on each of these devices is different. It would be desirable for the input plane device to be capable of inputting high contrast images at television rates, with erasure or write-over capabilities such that an image written on the input device at a television rate would be independent of previously written images. The input plane device should also be able to accomodate high resolution television images or images generated from multispectral scanners. The filter plane devices should also be capable of inputting high contrast, high resolution images to the filter plane of a Fourier optical processor, and in addition be capable of storing the image over an appreciable time interval. The filter function storage interval would be dependent on the application for which the processor is intended.

Four devices were considered in this investigation for the role of image input device. These were: (1) the General Electric Coherent Light Valve,

(2) the electron-beam-addressed KD*P light modulator, (3) the ITEK Pockel's Readout Optical Modulator, (4) and the Hughes Liquid Crystal Modulator. Of these four devices the PROM and the Liquid Crystal Modulator appear at this time to be the best candidates for real time optical processing applications because of their inherent operational simplicity, compactness, extended lifetime, and future development prospects. However, neither of these devices are completely satisfactory in their performance of the desired functions for an image input device and additional development work is required. Techniques for optimum systems applications of these devices should also be investigated.

Output plane detection devices provide another optical processor interface where device characteristics are important. The information in the output plane of an optical processor is in the form of a spatial distribution of light intensity. The detector should sample at discrete points or scan the output plane with sufficient resolution to extract the details of the processing operation. A review of solid state detection devices has been carried out, and the key characteristics of the various devices tabulated in Section III. The exact specification of an output plane device is dependent on the processor application, and should be selected on the basis of operational compatibility. A continuation of the digital simulation studies of optical processors discussed in Section VI will be necessary to establish the configuration of a suitable detector, and specify future development needs for these devices.

The mechanical design of an on-board optical processor is important to successful operation in a spacecraft mission. The general mechanical design considerations for an on-board optical procesor are discussed in Section IV. Guidelines have been suggested for establishing the mechanical specifications for an on-board optical processor designated for a specific mission.

The electronic interface with the optical processor is also not specifically defined at this time, but general interface considerations are discussed in Section V. Since it appears highly probable that the input to the optical processor will be an electrical signal in the form of a time waveform, and not a direct optical input, some unique electro-optical interface problems arise with the potential image input devices. The excitation for the input devices is generally an incoherent light image which must be generated from the time waveform representing the input signal to the processor. Section V presents a discussion of potential electrical-to-optical interface devices such as cathode ray tubes, storage tubes, and modulated laser beams. Imaging of these electrical-to-optical interface devices in the input plane of the incoherent-to-coherent input devices is also discussed. Recommendations concerning the interface electronics at this time are, that since there are so many unknowns in both the electrical-to-optical and optical input devices, a laboratory breadboard should be constructed to provide a test bed for the evaluation of real time input techniques.

Section VI presents a preliminary digital simulation of several potential problems relating to real time operation of an optical processor. Specifically considered were the optical correlation of two input images by the spatial heterodyning technique, and the effects of image decay on the correlation plane light intensity distribution. The results of this preliminary investigation strongly suggests that additional simulation studies be performed to evaluate the correlation signal degradation for complex coherent images which are subject to image decay resulting from the short relaxation times characteristic of some coherent input devices. These advanced studies would also serve to define the required parameters for the correlation plane detector.

From the results of this study it is recommended that the next phase of an on-going program leading to the development of an on-board coherent optical processing system be mission-oriented, and include the following elements: (1) select a specific spacecraft mission for which an on-board optical processor would significantly improve data management operations, and provide additional benefits in the reduction of system cost and complexity, (2) continue digital simulation of optical processing operations to define system requirements, (3) initiate the development of or modification to a real time optical input device which would be compatible with the spacecraft sensors for the selected mission, and (4) assemble a breadboard optical processor to allow experimental evaluation of the complex electrical-to-optical and optical-to-electrical interfaces.

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A-1719

FINAL REPORT

Project A-1719

CONCEPTUAL DESIGN OF AN ON-BOARD OPTICAL PROCESSOR WITH COMPONENTS

J. R. WALSH, R. G. SHACKELFORD

CONTRACT NAS8-31344

Prepared for
NATIONAL AERONAUTICS & SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA

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Engineering Experiment Station
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ABSTRACT

This report summarizes the investigation performed on Contract NAS8-31344. The objective of the first part of this investigation was the specification of components for a spacecraft on-board optical processor. The objective of the second part of the research program was the search for a space oriented application of optical data processing and the investigation of certain aspects of optical correlators. The investigation confirmed that real-time optical processing has made significant advances over the past few years, but that there are still critical components which will require further development for use in an on-board optical processor. The most critical component for a real-time optical processor is the real-time optical input device. A major part of the first part of this program was the collection and evaluation of information on these devices. The devices evaluated were the General Electric Coherent Light Valve, the ITEK Pockel's Readout Optical Modulator, the Hughes Liquid Crystal Modulator, and the Image Forming Light Modulator. The ITEK PROM and Hughes Liquid Crystal devices were identified as the primary candidates for the real-time input device of an optical processor although neither device could be judged at this time as completely satisfactory for the subject application.

During the second part of this program contact was made with personnel knowledgeable with future space missions and their data management requirements. The results of these discussions revealed that there is a hesitancy to do any on-board data processing because of the possible loss of some of the available radiometric data. The data handling philosophy is to transmit all of the data to earth and let each investigator reduce the data as he desires. Further, the prevailing thoughts were that if on-board processing were used it would be digital rather than optical at this time. This view is held because of the excellent outlook for on-going development of digital processing technology, and the large amount of support it is currently receiving. Because of formidable ground data storage problems, however, the reluctance toward on-board data processing may be set aside in the near future.

If this turn around occurs, optical processing systems will be competitive with digital systems for some applications because of their potentially lower acquisition cost and smaller input power drain, and their vastly superior processing speed.

Certain aspects of optical correlators are reviewed, and a brief discussion of the techniques for calculation of Fourier transforms by digital methods is presented.

PREFACE

This report covers work performed under Contract NAS8-31344 for the period 9 January 1976 through 9 January 1977 and briefly reviews work performed during the first part of the program from 10 March 1975 to January 1976. It is the culmination of a study of the application of coherent optical processing to on-board satellite data management systems, and represents the final report on the research program under Contract NAS8-31344. This program was performed under the technical cognizance of Messrs. J. H. Kerr and H. F. Smith, Code EF13, NASA-Marshall Space Flight Center, and their interest throughout this study is gratefully acknowledged.

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I. INTRODUCTION

This research program, Conceptual Design of an On-Board Optical Processor with Components, was divided into two parts performed sequentially. Part one dealt with the problems associated with the design of a satellite optical data processor, and part two was concerned with the applications of state-of-the-art optical processors to satellite data acquisition systems.

The results of the phase one effort were reported in the interim report [1-1]. In general that report presented a review of the status of selected components of an optical processor, a general discussion of the mechanical and electronic considerations of an on-board optical processor, and a digital simulation of the operational characteristics of real time optical processors.

Optical data processors derive their usefulness from the fact that a lens system can provide a two dimensional Fourier transform of an input image in the time it takes light to propagate through the optical system. Coherent optical data processing has existed since the early 1950's when many of the basic concepts were published [1-2, 1-3, 1-4, 1-5]. A major drawback to optical data processors in the past has been the limitations imposed by available techniques for inputting an image into the optical system. Photographic film has, for many years, provided the standard input medium. Recent developments in input devices for optical processors have put the optical data processor on the verge of real time operation. Four devices emerge as the principal contenders for real time input devices for optical processors. These are: (1) the General Electric Coherent Light Valve [1-6], (2) the KD*P Light Modulator [1-7], (3) the Hughes Liquid Crystal Modulator [1-8] and (4) the

Itek Corporation's Pockel's Readout Optical Modulator [1-9]. None of these devices function as an ideal input device and their selection must consider the intended application. The interim report discussed each of the devices and also presented a discussion of some of the interface problems presented by various parts of an optical processor.

The second part of the research program which makes up the main portion of this report was concerned with some aspects of optical correlators which apply to satellite data acquisition systems. The major portion of the effort was the search for a space oriented application of optical processors. Laboratory and industrial applications of optical and optical-digital data processors are numerous and many are discussed in this report. Space applications, however, are not as easily identified because of uncertainties in the accuracy and storage requirements of satellite acquired data.

During the second phase of this program project personnel held discussions with many people knowledgeable in future space missions and their data processing requirements. The current feeling toward on-board processing is one of reluctance to reduce the general applicability of the data to a wide range of user interests. There is a strong desire to transmit all the data to earth to be stored since on-board processing would result in the loss of some of the available data. If all data is transmitted, individual investigators can determine which parts of the data may be eliminated for their particular application.

Another strong consideration concerning on-board processing is the general feeling that if on-board processing were to be used it would probably be digital rather than optical for the first generation systems, for reasons discussed in Section II of this report.

There is a strong feeling that many processing applications presently performed by optical processors will in the not to distant future be performed by digital processors. It is our view, however, that economic and technological analysis must be applied to each data processing application to determine the merits of the two general processing techniques, and in some applications the most cost effective system may well be a hybrid optical-digital processor. As a result of this philosophy, a review was made of the digital processing techniques for linear transformations, and the results of recent technology extending optical processing techniques to nonlinear applications was also considered.

In general this report includes a review of the general applications of optical data processors, a brief review of components critical to optical data processors, and a review of competitive digital processing techniques for the generation of Fourier transforms.

II. APPLICATIONS OF OPTICAL DATA PROCESSORS

A. General Applications

Most optical computing systems are based on the Fourier transforming properties of a simple lens [2-1]. The ability of a simple lens to produce a two-dimensional Fourier transform has been known for years. Such processing systems offer the potential of extremely fast processing times and extremely large space-bandwidth products. Optical processing systems, however, do have some performance limitations. Since such systems are analogue in nature they process data with limited accuracy in comparison with the accuracy obtainable with digital systems. Flexibility is also limited since optical processors can perform linear operations such as the Fourier transform and correlation and convolution operations extremely fast but they are not easily modified to perform other computations. Work is presently underway to increase the flexibility of optical processors to include many new types of data processing operations. Among the methods by which the flexibility is being extended are nonlinear data processing operations and space-variant linear data processing systems [2-2].

There are many applications for which the speed and accuracy of optical processing systems make them ideally suited. However, it was not until digital computer technology and optical systems were combined that optical computing systems became of general interest. Early optical-digital computing systems of the late 1960's were used for pattern recognition. For example, Lendaris and Stanley developed a large computer controlled diffraction pattern sampling system during this time period [2-3]. Their system was large, complex, slow, and costly. With the combined decrease in cost of minicomputers and lasers a diffraction pattern sampling system can be acquired today at a reasonable cost. In the early 1970's optical computing systems began to be considered for industrial applications. Jensen pointed out some of the potential applications in 1973 [2-4]. The techniques he discusses are based on diffraction pattern sampling rather than the more complicated holographic systems envisioned by many people at that time for optical computers. He points out that even relatively simple optical systems can reveal the precise dimensions of wires, fibers, and spherical objects. Defects in metal, plastic, or glass sheets may also be detected. Particles can be classified, and measurements of sharpness, roughness, hardness, and stress and strain can be made.

With the cost of both optical and digital components such as lasers and integrated circuits being reduced in the early 1970's, many laboratory and industrial applications of optical processors have emerged. Many of these applications have been enumerated by Kasdan and Mead [2-5]. Laboratory applications include various image processing techniques falling in the general categories of aerial image analysis [2-6, 2-7], X-ray analysis [2-8], photomicrograph analysis [2-9] and cell particle scattering [2-10].

Industrial optical digital processing systems now operating include needle point inspection systems, photomask line width measurements, cloth wearing inspections, and paper printability measurements. Noble and Penn point out several additional applications which are well suited for optical processors [2-11]. These include (1) a time waveform spectrum analyzer, (2) a beamformer which reconstructs radio astronomical images from a microwave antenna array, (3) a radar processor matched filter, and (4) a real-time side looking radar image reconstructor. Optical filtering techniques have also been used to advantage in the deblurring of images and image enhancement [2-12].

B. Space Applications

A major part of the effort during the second phase of the project was devoted to the investigation of space applications of optical or optical-digital data processors. With higher data rates expected from future spacecraft, the amount of data to be transmitted to the ground gets to be quite impressive if no on-board data processing is provided. Currently, the Landsat series of satellites, which are earth resource oriented,are expected to have data rates of the order of 10^{12} bits per day. This presents a formidable storage problem for ground-based data collection centers.

To get some feel for the data transmission, data processing, and data storage requirements of future spacecraft missions, the Summarized NASA Payload Descriptions published by Marshall Space Flight Center were reviewed [2-13,2-14]. These summaries cover both automated and sortie payloads. The results of the review which concerned mainly data processing and transmission requirements are shown in Table I and II.

One class of satellites which have extremely high data transmission rates and require image processing are the earth resource satellites of which LANDSAT D is a typical example. The data rate for this satellite is currently quoted as 10^{12} bits per day.

Based on this information, personnel at Goddard Space Flight Center who manage this satellite program were contacted to determine the possibilities for on-board optical processing to reduce the data transmission rate. These

TABLE I

Data Rates - Automated Payloads

Experiment Number	Title	Real Time Data Rate	Real Time Data Volume	Stored Data Rate	Stored Data Volume	Experiment Data Processing Required	Type of Processing
AS-01-A	Large Space Telescope	10^6 & TBD	TBD		TBD	TBD	
AS-02-A	Extra Coronal Lyman Exp.	4.3E4	1.779E.9	4.3E4	1.1682E10	Yes	Integrate and Correlate Data
AS-23-A	Medium Aperature Opt. Tel.	1E6 1024	2.048E9 8.85E7	1E6 1024	2.048E9 8.85E7	Yes	Photometric Meas per Star, Resolution enhancement, astrometric readout
HE-01-A	Large X-Ray Telescope Fac.	3.5E4 2E5	3.024E9 5.369E8	5E4 2E5	3.024E9 5.369E8	Yes	Successive Image Integration, enhancement and data correction, diagnosis
HE-03-A	Extended X-Ray Survey	64816 1E6	5.6E9 5.6E9	64816 1E6	5.6E9 5.6E9	Yes	Spatial Image and Dynamic Range Enhan. Rejection of Spurious Radiation Interference
HE-07-A	Small High Energy Satellite	40960	2.123E9	N/A	N/A	Yes	Exp. per. eval. data reduct. and correlation
HE-08-A	Large High Energy Obs. A (Gamma Ray)	2048 12048	4.42E7 1.041E9	2048 12048 2.12E5 1E6	4.44E7 1.041E9	Yes	Radiation and Spurious Count Removal Flux and Spectral vs. Spatial Location
HE-09-A	Large High Energy Obs. B (Magnetic Spectrometer)	12048 51200 1E6	1.041E9	12048 51200 1E6	1.041E9	Yes	Nucleon Identification, Spatial Track Correlation, energy level est. and diag.
HE-11-A	Large High Energy Obs. D (1.2m X-Ray Tel.)	3.5E4 2E5	3.024E9 6.16E9	3.5E4 2E5	3.024E9 6.16E9	Yes	Successive image integration enhancement and data correction; diagnosis
SO-03-A	Solar Maximum Mission (SMM)	1024KHz 9810	8.5E8 9.5E4Hz	768KHz 1.3E5	TBD	Yes	Real time Data evaluation
AP-01-A	Upper Atmos Exp.	1024KHz 9810	8.5E8 9.5E4Hz	768KHz 1.3E5		Yes	Real time data evaluation
AP-02-A	Explorer - Medium Altitude	1024KHz 9810	8.6E8 221Hz	768KHz 1.3E5		Yes	Real time data evaluation
AP-03-A	Explorer - High Altitude	1024KHz 9810	1.3E8 9.5E4Hz	768KHz 1.3E5	TLD	Yes	Real time data evaluation
AP-04-A	Gravity and Relitivity Satellite (LEO)	1000	7.3E6	2300	7.3E6	Yes	Real time data evaluation
AP-05-A	Environ. Perturbation Satelite A	2000 9E4	Analog TBD 1.73E8	TBD	TBD	Yes	Short time data evaluation
EO-08-A	Landsat-D (EOS-D)	4000 1.28E5 2E8 2E8	1.13E11	N/A	N/A	Yes	Image Processing
EO-10-A	Applications Explorer	N/A	N/A	2.8E5	8.6E8	Yes	Produce contour plots time correlated temp. maps, color pictures, etc.
EO-12-A	TIROS-O	VHF 1350Hz 1.2E5 2E8 4000	1.13E11	N/A	N/A	Yes	Image Precessing
EO-57-A	Foreign Sync. Meter Sat.	28E6 194 BPS 50000Hz 14E6	12E11	N/A	N/A	Yes	Meteorological Computations

TABLE I (continued)

Data Rates - Automated Payloads

Experiment Number	Title	Real Time Data Rate	Real Time Data Volume	Stored Data Rate	Stored Data Volume	Experiment Data Processing Required	Type of Processing
EO-58-A	Geosync. Oper. Environ. Satellite	28E6 194 BPS 50000Hz 14E6	12E11	N/A	N/A	Yes	Meteorological Computations
EO-61-A	Earth Res. Survey Oper. Satellite	1.5E8 4.5E6Hz	1E9 A45 Min/D	6E8 4.5E6Hz	1.E11 210 Min	Yes	Image Processing
OP-01-A	Geopause	1024	1E6	1.73E4	1.73E8		
OP-02-A	Gravity Gradiometer	400	35E6	N/A	N/A	No	
OP-03-A	Mini-LAGEOS	N/A	N/A	N/A	N/A	No	Totally Passive Laser Reflectors (Earthquake Assessment)
OP-04-A	Gravity Field Satellite	1000	2.9E9	15000	14.4E6	Yes	Support Proc. and Gravity Field Determination (Earthquake Assessment)
OP-05-A	Vector Magnetometer Sat. Satellite	1.5E5	12E7	1.5E5	Combined RT and PB 12E7	Yes	
OP-06-A	Magnetic Field Monitor Satellite	1.5E5	12E7	1.5E5	Combined RT and PB 12E7	Yes	
OP-07-A	SEASAT-B	N/A	N/A	9E7	3.6E10	Yes	
LS-02-A	Biomedical Exper. Scientific Satellite	TBD	TBD	TBD	TBD	No	
ST-01-A	Long Duration Exposure Fac.	N/A	TBD	TBD	TBD	Yes	To effect contamination counter-measures
PL-07-A	Venus Orbital Imaging Radar	TBD	TBD	TBD	TBD	Yes	Instrument Checkout
PL-12-A	Mariner Jupiter Orbiter	1.17E5 1.17E5	6E11	1.1E5	6E11	Yes	Instrument Checkout
PL-22-A	Pioneer Saturn/Uranus/Titan Probe	2048 2048	TBD	N/A	N/A	Yes	For Investigators
PL-28-A	Pioneer Mars Surface Penetrator	2048	TBD	N/A	N/A	Yes	For Investigators
CN-51-A	International Telecommunication Satellite	1000	8.64E7	N/A	N/A	No	
CN-52-A	U.S.-DOMSAT A	1024	8.85E6	N/A	N/A	No	
CN-53-A	U.S.-DOMSAT B	1000	8.64E7	N/A	N/A	No	
CN-54-A	Disaster Warning Satellite	600	5.25E7	N/A	N/A	No	
CN-55-A	Traffic Management Satellite	512	4.4E7	N/A	N/A	No	
CN-56-A	Foreign Communications Satellite- A	1000	8.6E7	N/A	N/A	No	
CN-58-A	U.S.-TDRS-C	1024	9E7	N/A	N/A	No	
LU-01-A	Lunar Orbiter	2E5	1.74E10	TBD	TBD	Yes	Instrumentation C/O and Short Term Data Analysis

TABLE II-1
Data Rates Sortie Payloads

Experiment Number	Title	Data Acquisition & Management			
		Science Data Acquisition			
		Rate	Volume	TV	Voice
AS-01-S	1M Shuttle IR Teles. Fac.	251830	1.434E9	24 hrs.	4kHz
AS-03-S	Deep Sky UV Surrey Teles.	(only housekeeping data)		1.6	5kHz
AS-04-S	1M Diffract. Lmtd, UV Opt. Tel.	1E7	2.88E9	1.6	5
AS-05-S	Very Wide Field Galactic Camera	(housekeeping only)		12.8	3
AS-15-S	3M Ambient Temp. IR Teles.	21740	1.468E9	24	Std.
AS-63-S	Sortie Med. Aperature Opt. Tel.	(housekeeping only)		16	5
HE-11-S	X-Ray Angular Structure	20480	8.05E9		
		10240	6.98E11		
		10240	6.98E11		
		43008	3.7E9	1.6	
HE-15-S	Magnetic Spectrometer	10000	8.64E8	-	
HE-19-S	Low Energy X-Ray Teles.	40960	3.54E9	-	-
HE-25-S	Transition Rad-Det. (HE-701)	1500	1.296E8	-	-
SO-01-S	Dedicated Solar Sortie Mission (DSSM)	1.32E7	5.94E11	-	4
SO-11-S	Solar Fine Pointing Payload	1.32E7	5.94E11	-	4
SO-15-S	Solar Activity Early Payload	5.77E6	2.60E11	-	4
SO 17-S	Solar Activity Growth Processes (SO-703)	1E6	8.6E10	1.5	4
AP-06-S	Atmos. Magnetospheric & Plasmas in Space (AMPS)	3.2E6	1.4E11		
		1.E7			
		4.E5	TBD		3200 b/s
AP-08-S	Lidar System (AP-701)	4800	1.1E8	-	-
AP-09-S	Electron Accelerator (AP-702)	D2920	2E5		
		A3000Hz	8.5 hrs.	-	-
			6000 Hz		
AP-10-S	Chemical Release (AP-703)	208	1.7E7	-	-
AP-11-S	Diagnostic Payload (AP-704)	D3E5	6E9	-	-
		A 20 MHz	120 MHz		
AP-12-S	TADS (AP-705)	D TBD	24 hrs.	-	-
		A 10 MHz	20 MHz	-	-

TABLE II-1 (continued)
Data Acquisition & Management (continued)

Experiment Number	Function	Computer Support			
		Mem(R/A)	Mem(BULK)	Word Length	Operations Per Sec
LS-04-S	Data Formatting	24000	5.E4	16	1E5
LS-09-S	Warefan Analysis Data Comp. Trad				
LS-10-S	" "	24000	5E5	16	1E5
LS-13-S	" "	13000	5E4	16	1E5
EO-01-S	Data Formatting Data Storage	2500	1500	24	1E5
EO-05-S	Formatting and Storage	9000	200	16	30000
EO-06-S	Monitor and Format Data	2000	1500	7	120
EO-19-S	TBD	TBD	TBD	TBD	TBD
EO-20-S	Pointing Central	TBD	TBD	TBD	TBD
EO-21-S	TBD	TBD	TBD	TBD	TBD
EO-22-S	TBD	TBD	TBD	TBD	TBD
OP-02-S	Data Formatting, Storage Commands, Computations	5E3	2000	10	7E4
OP-03-S	Telescope OP-102 Pointing controls	5400	2000	16	29000
OP-04-S	Comm. Exp., Monitor Exp. Format Data For Storage	7.6E3	2000	10	2.9E4
OP-05-S	Data Formatting, Data Storage, Computations	5E3	2000	10	7E4
OP-06-S	" "	5E3	2E6	10	1.9E4
SP-01-S	N/A	N/A	N/A	N/A	N/A
SP-14-S	N/A	N/A	N/A	N/A	N/A
SP-15-S	No	N/A	N/A	N/A	N/A
SP-31-S	N/A	N/A	N/A	N/A	N/A
ST-08-S	TBD	TBD	TBD	16	TBD
ST-31-S	N/A	N/A	N/A	N/A	N/A
CN-05-S	N/A	N/A	N/A	N/A	N/A
CN-08-S	N/A	N/A	N/A	N/A	N/A

TABLE II-1 (Concluded)
Data Disposition & Communications (Continued)

	Digital (Continued)		Television			
	Dump 1 Day	Shuttle Sto & Ret	RT	Dump 1 Orbit	Dump 1 Day	Sto & Ret.
AS-01-S	1.844 E9	1.1117E10	26 MHz	26 MHz	26 MHz	26 MHz
			0.174 hrs.	0.858 hrs.	13.3 hrs.	16 hrs.
AS-03-S	2.59E8	1.555E9	26 MHz	26 MHz	26 MHz	26 MHz
			0.1 hr.	0.1	1.6	9.6 hr.
AS-04-S	3.053E9	5.400E9	26 MHz		26	26
			0.1	0	1.6	9.6
AS-05-S	N/A	1.298E9	1E6 Hz			1E6 Hz
			0.8	N/A	N/A	76.7 hr.
AS-15-S	1.88E9	1.117E10	26	26	26	26
AS-63-S	0	1.73E8	0.1	0.1	1.55	9.2
			26		26	26
			0.1	0	1.55	9.1
HE-11-S	3.7E9	2.2817E10	0.1	0.1	1.6	9.6
HE-15-S	1041	6.246E9	N/A	N/A	N/A	N/A
HE-19-S	3.64E9	2.3000E10	N/A	N/A	N/A	N/A
HE-25-S	1.38E8	8.99E8	N/A	N/A	N/A	N/A
SO-01-S	5.94E9	N/A (P/L Tape Rec.)	0	0	0	0
SO-11-S	5.94E10	N/A (P/L Tape Rec.)	0	0	0	0
SO-15-S	2.6E9	N/A (P/L Tape Rec.)	0	0	0	0
SO-17-S	7.3E9	4.400E10	TBD	N/A	N/A	5E6 Hz
AP-06-S	TBD	TBD	TBD	TBD	TBD	9.3 hr.
AP-08-S	TBD	TBD	TBD	TBD	TBD	TBD
AP-09-S	TBD	TBD	TBD	TBD	TBD	TBD
AP-10-S	N/A	1.7E7	N/A	N/A	N/A	N/A
AP-11-S	TBD	TBD	TBD	TBD	TBD	TBD
AP-12-S		20M	TBD	TBD	TBD	TBD

TABLE II-2

Sortie Payloads (continued) — Data Acquisition & Management

Experiment Number	Title	Science Data Acquisition: Rate	Volume	TV	Voice
		Digital And TV Totally Handled By FFTO Systems			
LS-04-S	Free Flying Teleoperator				
LS-09-S	Life Sciences Shuttle Lab'ry.	23.6E3	2.04E9	(1.5)	TBD
				(12.)	
LS-10-S	Life Sciences Mini-Labs	7E3	6.18E8	6E6(COLOR)	INTERM.
LS-13-S	Life Sciences First US/ESRO Spacelab Mission (LS-701)	7E3	50E6	6E6(COLOR)	INTERM.
EO-01-S	Zero-G Cloud Physics Lab. (EO-701)	1E5	160E6	2	-
EO-05-S	Shuttle Imaging Microwave Syst (SIMS-1B)	5ES	9.2E9	0.6	-
EO-06-S	Scanning Spectroradiometer	220	2.61E6	-	-
EO-19-S	Mark II Interferometer-Solar (EO-703)	130E3	5.62E8	-	-
EO-20-S	Earth Resources Shuttle Imaging Radar (EO-704)		1.056E13	-	-
EO-21-S	Shuttle Imaging Microwave System (SIMS-A)	1.5E6	8.7E10	-	-
EO-22-S	Mark II Interferometer-Earth	1.3E5	1.4E9	-	-
OP-02-S	Multifrequency RadarLand Imagry (OP-702)	2.66E5	8.55E9	-	-
OP-03-S	Multifrequency Dual Polarization	4000	1E8		
	Microwave Radiometer (OP-703)	22,000	NIA	-	105 hrs.
OP-04-S	Microwave Scatterometer	2.82E4	7.614E8	-	-
OP-05-S	Multispectral Scanning Imagry	2.64E5	8.55E9	-	-
OP-06-S	Laser Altimeter/Profilometer Exp.	29340	1.01E9	-	-
SP-01-S	SPA No. 1 Biological (Manned) (B+C)	94	2.44E6	4.2MHz 3 hrs.	-
SP-14-S	SPA No. 14 Manned & Automated (B+G+C+FP+LP)	14300	564E6	4.2 M 3 hrs.	-
SP-15-S	SPA No. 15 Automated Furnace/Levitation (FP+LP+CP)	14000	484E6	-	-
SP-31-S	Biological/Furnace Subelements & Core (SP-701/702)	30	4.08E6	-	-
		30	2.59E6		
ST-08-S	IRTCM (Integrated Real Time Contammation Moniter)	97E3	8.4E9	-	-
ST-31-S	Drop Dynamics Facility (ST-703)	1000	3.6E6	-	-
CN-04-S	Electromagnetic Environ Expt. (CN-701)	Experiment will Transmit 15.E6 b/s of Experiment Data To Ground Via TDRS For Approximately 0.2 hr Per Orbit.			
CN-05-S	CO2 Laser Data Relaylink (CN-703)	3000	5.4E6	3	-
CN-08-S	TWT Opern Envelope Expts. (CN-704)	488	4.21E7	5	-
		72	6.2E6		

TABLE II-2 (Continued)

		Data Acquisition & Management (Continued)				Data Disposition & Communications		
		Computer Support				Digital		
Number	Function	Mem(R/A)	Mem(BULK)	Word Length	Operations Per Sec	RT	Time Dump	1 Orbit (Cent)
AS-01-S	Data Qual. Comp.		80000	32	80000			
	Auto Mon & Cont.		20000		20000	256000	1.55 hrs.	1.21E8
AS-0S-S	Data Formatting			32		3000	1.5	16.2E6
AS-01-S	Data Formatting, Curuefit,							
	Transformations Etc.	8000	5E5	32	5E4	1E7*	1.5	190.8E6
AS-05-S	G & N Pointing	4000	5E4	32	4000	2500	1.5	N/A
AS-15-S	Comp. Mon. Cont.	8000	5E5	32	50000	21740	1.55	1.21E8
AS-63-S	Transformations							
	pseudo color displays	8000	5E5	32	5E4	2000	1.5	-
HE-11-S	Various Housekeeping	8000	6.4E4	32	2E4	43008	1.5	2.32E8
HE-15-S	Data Qual. Cont.							
	(Normally Done on Earth)	32000	1E6	32	3.6E4	12048	1.5	6.5E7
HE-19-S	Quick look data processing	4000	5E4	32	4000	42120	1.5	2.274E7
HE-25-S	N/A	N/A	N/A	N/A	N/A	1600	1.5	8.64E6
SO-01-S	TBD	TBD	TBD	TBD	TBD	1.32E6	0.833	3.9E9
SO-11-S	TBD	TBD	TBD	TBD	TBD	1.32E6	0.833	3.9E9
SO-15-S	TBD	TBD	TBD	TBD	TBD	5.77E6	0.83	1.7E9
SO-17-S	Pointing Control	8000	5E5	32	10000	1E6	1	N/A
AP-06-S	Prediction Analysis							
	Spectrum nalysis	300 to	2500 to					
	Data Reduction, RT data Storage	4000	12000	32	32000 max.	TBD	TBD	TBD
AP-08-S	Pointing & Control	TBD	TBD	TBD	TBD	TBD	TBD	TBD
AP-09-S	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
AP-10-S	Pointing Calc.	TBD	TBD	TBD	TBD	N/A	N/A	TBD
AP-11-S	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
AP-12-S	Positions							
	Data Analysis	TBD	TBD	TBD	TBD	TBD	TBD	

TABLE II- 2 (Concluded)

DATA DISPOSITION & COMMUNICATIONS

Experiment Number	Digital RT	Digital Time	Digital Dump 1 Orbit	Digital Dump 1 Day	Digital Shuttle Sto & Rot	TV RT	TV Dump 1 Orbit	TV Dump 1 Day	TV Sto & Ret.
LS-04-S	3840	.2	N/A	N/A	N/A	2	N/A	N/A	N/A
LS-09-S	14E3	0.5	N/A	2.16E5	1.34E5	6E6Hz 0.5 Hr.	0.75	N/A	6 MHz 7.5 Hr.
LS-10-S	TBD	TBD	N/A	6.18E8	4.2E3	6E6 0.25	 N/A	6E6 0.25	6E6 4
LS-13-S	TBD	N/A	N/A	50E6	3.52E7	6E6 Hz 0.25 Hr.	N/A	6E6 0.25	6E6 3
EO-01-S	0	0	0	0	8E8	4E6 Hz 0.25 Hr.	 N/A	 N/A	 N/A
EO-05-S	0	0	0	1E7	4.59E10	0	0	0	4.63E6 3.41 Hrs.
EO-06-S	N/A	N/A	N/A	N/A	1.43E7	N/A	N/A	N/A	N/A
EO-19-S	N/A	N/A	N/A	N/A	3.37E9	N/A	N/A	N/A	N/A
EO-20-S	N/A	N/A	N/A	N/A	1.98E8	N/A	N/A	N/A	N/A
EO-21-S	0	0	1E9	1E7	0	0	TBD	0	0
EO-22-S	N/A	N/A	N/A	N/A	1.404E9	N/A	N/A	N/A	N/A
OP-02-S	2.66E5	0.1	9.6E7	8.62E9	4.3E4	0.2	0.2	0.2	1
OP-03-S	0	0	0	100E6	5.0E8	0	0	0	0
OP-04-S	0	0	0	0	1.242E9	0	0	0	0
OP-05-S	2.66E5	0.1	9.6E7	8.62E9	4.3E4	0.2	-	0.2	1
OP-06-S	3.42E4	0.1	0.7E4	1.4E8	5.54E3	N/A	N/A	N/A	N/A
SP-01-S	94	1.8	N/A	N/A	N/A	4.2M 0.75	N/A	N/A	4.2M 8
SP-14-S	1.43E4	4.0	N/A	6.18E8	2.47E3	4.2M 0.75	N/A	N/A	4.2M 8
SP-15-S	1.4E4	0.2	N/A	5.56E7	2.779E9	N/A	N/A	N/A	N/A
SP-31-S	0	0	0	0	4.57E7	N/A	N/A	N/A	N/A
ST-08-S	N/A	N/A	84E8	8.4E9	5.47E10	N/A	N/A	N/A	N/A
ST-31-S	N/A	N/A	N/A	3.6E6	1.8E7	N/A	N/A	N/A	N/A
CN-05-S	N/A	N/A	N/A	N/A	6.3E7	N/A	N/A	N/A	N/A
CN-08-S	0	0	0	9.7E6	2.988E8	N/A	N/A	N/A	N/A

discussions revealed that at least for this generation satellite, on-board data processing of any type was not being considered. This decision is based on the philosophy that on-board data processing would result in the loss of radiometric information which would reduce the attraction of LANDSAT to some of its potential users. Since the parts of the collected data which may be discarded cannot be determined to suit all the users simultaneously, the philosophy is to transmit all of the data to the ground and store it for future reference and processing at the user's discretion. This allows each investigator to process the data as he desires, discarding parts of the data which are unimportant to him. Such a plan will provide a large data base for many investigators at the expense of a very large data transmission and storage problem.

Even if on-board processing were being considered, the present thoughts are that it would be digital rather than optical. There are several primary reasons cited for this preference; (1) greater dynamic range of digital processors, (2) higher accuracy obtainable with digital processors, (3) flexibility of digital processors, and (4) the future outlook for digital versus optical processors. While these considerations are valid for serial processing applications, the optical processor is still far superior for processing large quantities of data in parallel.

The dynamic range of digital processors is essentially limited by the number of bits used to represent a number and can be very large (typically about 48 dB for 16 bits). Thus, the digital processor can easily be made to have a greater dynamic range than the sensor which is the source of the data.

Processing accuracy of a digital processor can also be made quite good by using such techniques as double precision processing. Care must be taken, however, since the large number of operations required by a fast Fourier transform algorithm, for example, may result in degradation of the accuracy of the calculations.

Flexibility of a digital processor is greater than that of an optical processor. An optical processor essentially performs the Fourier transform operation by making use of the light diffracting property of a lens. Some techniques, such as nonlinear system operations, are presently being used to extend the flexibility of optical processors. Even with these techniques, there is a limited range of flexibility available with optical processors. On the other hand, a stored program digital computer can perform a wide range of operations, depending only on the ingenuity of the programmer to generate the algorithms to perform the desired operations and the storage capacity required to implement them. Over the last two decades a wide variety of algorithms for digital computers have been developed. Although a direct comparison is difficult because of their widely different processing capabilities, an optical processor is potentially much less expensive than a large scale or special purpose digital processor.

One important feature of optical processors should not be overlooked. This feature is the speed and bandwidth available from optical processors. An optical processor using a simple lens can produce the Fourier transform of a high resolution imput image in the time required for light to propagate through the processor. Some of the LANDSAT images, for example, may approach as many as 4000 resolution elements along one scan line of the image. When such high resolution images are involved, the time required to produce a

Fourier transform digitally using the fast Fourier transform and high speed matrix transposition techniques can be excessive. There should be applications where the speed of the transform operation available from the optical systems outweighs the accuracy and dynamic range advantages of digital systems. An example of such an application would be real time image processing for spatial or texture analysis in which both on-board buffer storage and ground storage requirements could be significantly reduced.

Contact with personnel of the Johnson Space Center in regard to the high data transmission requirements of the Space Shuttle Imaging Radar also revealed a preference for digital data processing. The same basic reasons were cited as for LANDSAT processing with one important consideration being a dynamic range of 50 dB. Even though digital data processing is preferred, optical data processing for this application has not been completely ruled out if a system can be shown to be competitive in dynamic range and power requirements.

The future outlook for digital systems appears to be quite good. This is a result of the large amount of money which continues to be put into the development of such systems. By comparison, a very small amount of funding has gone into the development of optical processing systems. In our view, this situation will not change until spacecraft image processing requirements exceed the expectation of digital processing systems. The projected requirements of the LANDSAT follow-on, a maximum information per image of 2×10^9 bits and a maximum accumulation of 10^{12} bits/day, may result in the investigation of alternative processing and storage techniques.

III. REVIEW OF COMPONENTS CRITICAL TO REAL TIME PROCESSORS

A. Introduction

Since the coherent optical processor is an analogue device, its successful application will be found in special purpose processing systems for which definite advantages over digital computing systems can be demonstrated. For on-board satellite applications, desirable system improvements would include reduction in equipment complexity or power requirements, reduction of RF downlink bandwidth through on-board data compression, and improvements in automatic navigational or docking systems.

The coherent optical processor operates in parallel with the number of parallel channels equal to the number of resolution cells at the input modified by the system modulation transfer function (MTF). A linear transformation can be performed on all these parallel inputs simultaneously; however, the most commonly used input recording medium, photographic film, does not allow real time processing. Even the coherent optical synthetic aperture processors, which employ mono-bath processing techniques, require several minutes between exposure of the film and the useable transparency.

It is clear, therefore, that the most critical component in the coherent optical processor is the real time input device. Over the last five years, a number of devices have been developed around electro-optic crystals, liquid crystal films, ferroelectric ceramics, thermoplastic films, and deformable membranes. On-going development of many of these devices has been stopped because of technical barriers which were too costly to overcome or because of the emergence of other clearly superior device technology.

During the course of this investigation, visits were made to ITEK, Hughes, and General Electric to obtain information on the latest developments in coherent modulator technology, and to observe first hand the performance of the respective devices mentioned above. The impressions gained through these visits supplemented with operating experience on an IFLM which was fabricated at Georgia Tech under contract NAS8-27375 [3-1] form a basis for the information contained herein.

In considering the application of coherent optical processors to on-board spacecraft systems, we will assume that the optical components will be required to satisfy the environmental constraints of spacecraft environment, and that the performance of these components will be compatible with the image quality presently obtained from the ERTS MSS sensor. It has been assumed that optical lens fabrication and coating technology is sufficiently advanced to allow realization of the lens components required for the development of the optical processing systems considered in this report. Hence, the primary emphasis of this study has been directed toward the investigation of real time coherent input devices and detector arrays for sampling and processing the optical processor output plane distribution.

B. Real Time Input Devices

An ideal coherent optical input device would spatially modulate a coherent optical beam to create a phase and amplitude image replica of high resolution and very low distortion which could be instantaneously altered to form new images or stored indefinitely to be used as a permanent image transparency. Practical devices deviate from these ideal characteristics in image quality, time interval required to change the image, and length of time the image can be stored without image degradation. Although some of the devices surveyed exhibited excellent performance in one or perhaps more of the desired characteristics, no device was found to perform well in all categories.

Although this study was not oriented toward a specific spacecraft application, the field of candidate devices can be significantly narrowed by relating potential processing tasks to two common image formats. The ERTS multispectral scanner (MSS) sensor generates a complete image frame consisting of 2313 x 2313 resolution cells at the rate of one image every 28.7 seconds. High resolution vidicons, on the other hand, are capable of generating images with about 1000 x 1000 picture elements at a rate of 30 Hz. Very high resolution tubes with large sensor formats are capable of 10,000 line resolution in a 50 by 50 mm format [3-2]. We have, therefore, restricted our attention to devices which appear to have the potential for achieving image quality compatible with multispectral scanners and are capable of operating at television rates.

The first screening of coherent optical input devices for on board satellite optical processing applications yielded five potential device technologies. These potential technologies are represented by the ITEK Pockel's Readout Optical Modulator (PROM) [3-3, 3-4, 3-5, 3-6], the Hughes Photoactivated Liquid Crystal Light Valve [3-7, 3-8, 3-9, 3-10], the Image Forming Light Modulator (IFLM) [3-1], the General Electric Coherent Light Valve (CLV) [3-11, 3-12] and the CBS Lumatron [3-13]. Of these, the IFLM, CLV and the Lumatron are modified cathode ray tubes, whereas the PROM and the Liquid Crystal Modulator are very compact devices which operate in an open environment. The CRT type modulators have the advantage of simple electronic interface with the image signal representation of the TV sensor. In all three devices, spatial modulation results from an electron charge distribution which is deposited on the crystal by a scanning electron beam. The IFLM exploits the Pockel's effect in the electro-optic crystal KD*P, while the CLV and Lumatron are phase modulated by surface deformations in thin thermoplastic films.

The IFLM was initially eliminated from further consideration for this application on the basis of poor image quality, relatively short lifetime, and system complexity; however, it was recently reported by Casasent [3-14] that a lifetime of 3 years was being projected for a KD*P modulator developed at Carnegie Mellon University. Although the response time of the IFLM is excellent and its operating mode is well suited for the TV sensor, its image quality is barely sufficient for this application. The resolution is limited to about 20 lines/mm because of electric field fringing in the KD*P plate. The current state-of-the-art in the crystal technology limits the size of good quality KD*P plates to about 2 inches, which results in a maximum of about 1000 resolution elements along each dimension of the plate. The modulator discussed by Casasent utilized a 1" x 1.5" 6 mil thick plate with a higher spatial resolution (37 lp/mm), but with the same number of resolution cells (1000 x 1000). In addition, this resolution can only be achieved if the crystal is cooled to near its Curie point which is about -55° C. The lifetime of the KD*P modulator is also questionable because of the surface degradations associated with the intense electron beam required for full contrast. The lifetime of the electron gun cathode is severely reduced when operated at the required beam current of $2A/cm^2$. These considerations along with the complexity associated with the modulator cooling requirement cause the IFLM device to be rated well below the leading contenders.

The Lumatron solid film thermoplastic modulator was eliminated from consideration because of its slow recycle time. Although good images are possible with this device, a complete write-erase cycle requires several seconds.

C. Comparison of PROM, CLV, KD*P, And Liquid Crystal Modulators

A comparison of imaging and system performance characteristics for the PROM, CLV, and Liquid Crystal Modulator is given in Tables III-1 and III-2. For a detailed discussion of the physical characteristics and operating modes of these devices see Section III of the Interim report

D. Summary of Optical Input Device Characteristics

In summary, the final choice of a coherent optical input device for on-board spacecraft data processing applications will be strongly influenced by the type of image sensor employed and the processing operations required for the application. In general, the PROM and Liquid Crystal Modulator appear to offer greater potential for spacecraft applications because of their good image quality, compact size, and long lifetime. The CLV, on the other hand, has lower complexity interface requirements, and exhibited the highest image quality of the candidates. Its poor lifetime, large size and questionable adaptability to a space environment form the primary basis for ranking the CLV behind the PROM and the Liquid Crystal Modulator. The KD*P modulator has questionable lifetime, relatively poor image quality, and significant materials problems which, in our view, place it a distance last among the candidate devices which have been considered. A summary of considerations relating to the selection of the PROM or the Liquid Crystal Modulator for a given optical processing application follows.

TABLE III-1

Comparison of Coherent Image Performance for the
PROM, CLV, KD*P, and Liquid Crystal Modulator

	Photometric Sensitivity	Resolution	Active Area	No. of Resolution Cells	Contrast	Gray Scale No. of Steps for $\Delta D=0.15$	Isolation Read-Write	Input Dynamic Range
GE CLV	N.A.	25 lp/mm @ 50% MTF	1"x 1"	625 x 625 @ 50% MTF	10^5:1	14	∞	21 dB
Itek PROM	300 ergs/cm^2 for C=100:1 10^4 ergs/cm^2 for C=10^4:1	50 lp/mm* @ 50% MTF	1"x 1"	1,250 x 1,250 @ 50% MTF	10^4:1	27	28 dB	40 dB
Hughes Liquid Crystal Modulator	160 μW/cm^2 for C=100:1	60 lp/mm @ 50% MTF	1'x 1"	1,500 x 1,500 @ 50% MTF	10^2:1	9	50 dB	15 dB
KD*P Carnegie Mellon	N.A.	20 lp/mm † @ 50% MTF	2"x 2"	1,000 x 1,000	10^2:1		∞	

* Much greater resolution is possible for images possessing a narrow spatial frequency spectrum.

† Requires cooling to the Curie temperature of KD*P (∿ 50° C).

TABLE III-2

Comparison of System Performance Characteristics for
the PROM, CLV, KD*P, and Liquid Crystal Modulator

	Response Time	Cycle Rate	Storage Time	Maximum Light Output	Drive Requirements	Lifetime	Level Slicing	Estimated Cost
GE CLV	4 msec.	30 Hz	<300 msec.	700 Lumens	7000 Vdc @ 10 μA	1,000 hrs.	No	$75 K
Itek PROM	.01-100 * μsec.	60 Hz	<1 hour †	limited by Read-Write Isolation	2000 Vdc	>10,000 hrs.	Yes	$38 K
Hughes Liquid Crystal Modulator	10-250 msec.*	15 Hz	N.A.	1,000 Lumens	6 Vac @ 0.5 mA	>10,000 hrs.	Yes	$25 K
KD*P Carnegie Mellon	5 μsec.	30 Hz	1 hour			?	No	

* Response time is dependent on the writing intensity.

† Maximum storage time cannot be realized for continuous read-out because of image degradation resulting from low read-write isolation.

ITEK PROM

Advantages

1. Compact Size
2. Good Image Quality (High Resolution, High Contrast, High Input Dynamic Range)
3. Compatible with TV Sensor
4. Has Storage Capability
5. High Sensitivity
6. Has Level Slicing Capability
7. Controllable Image Erase Capability

Disadvantages

1. Requires High Voltage Supply for Operation
2. Low Read-Write Isolation
3. Long Range Improvements Depend Primarily on Developing New Electro-Optic Crystals
4. Requires Electrical-to-Optical Interface

Hughes Liquid Crystal Modulator

Advantages

1. Compact Size
2. High Resolution
3. Low Drive Power Requirements
4. Potentially a Low Cost Device
5. High Read-Write Isolation
6. Has Level Slicing Capability
7. Long Range Improvements Depends Primarily on Well Established Thin Film Technology

Disadvantages

1. Low Contrast and Input Dynamic Range
2. Slow Response and Decay Times
3. Cosmetic Quality of Images is Poor
4. Alignment of Liquid Crystal Film can be Destroyed by Mechanical Shock
5. Requires Electrical-to-Optical Interface

E. Correlation-Plane Detector Requirements

There are specific requirements for the physical characteristics of a detector to be used in the correlation plane of an optical processing system. These requirements are reviewed here and a discussion of detector characteristics appears in Section III-F in the Interim report. The correlation plane requirements are then compared with available detector characteristics.

The information in the correlation plane is in the form of a spatial distribution of light intensity. The detector should, therefore, sample at discrete points or scan the area covered by this distribution. For example, the use of an array of discrete elements, the outputs of which can be electronically scanned, enables near real-time processing to be achieved. This mode of operation would be virtually impossible to accomplish by physically scanning the light distribution with a single detector element. Even with electronic scanning of a fixed array, the response time of the detectors must be minimized.

The light intensity can vary large amounts over small distances. Therefore, detector elements with a wide dynamic range and small size are required. Likewise, the intensity patterns of interest may vary by relatively small amounts over large distances. This possibility requires highly stable detectors with a wide dynamic range.

With a laser as the source in an optical processing system there is usually more than enough power available to saturate the detector elements in the high intensity regions of the information plane. However, some incoherent-to-coherent input devices are capable of contrast reversal operations which can be employed to reduce the undiffracted component of the Fourier transform diffraction pattern by a factor of 10^4. In this case, the dynamic range requirements are greatly reduced. The major consideration is then a lack of adequate sensitivity in the regions of low light level. In summary, the requirements for a correlation plane detector are that it consist of an array of very sensitive, highly stable, and fast detector elements that respond linearly with irradiance over a wide dynamic range. The arrays must be capable of being fabricated in a variety of sizes and configurations with adequate resolution for the optical data processing application.

F. Available Detector Arrays

The most promising detectors for use in the correlation plane of an optical processing system are the solid state devices of the following types:

1. Photodiode arrays,
2. FET bucket brigade,
3. Charge coupled devices (CCD's), and
4. Charge Injection Devices (CID's)

G. Comparison of Correlation Plane Detectors

Table III-3 presents a comparison of the correlation plane detection devices.

TABLE III-3

TYPICAL PARAMETERS FOR ARRAY DETECTORS

Device	Array Configuration	Element Spacing	Illumination Sensitivity	Dynamic Range	Response Time	Frame Rate	Random Access
Reticon	Linear and Rectangular-Self Scanning Photodiode Array	linear-1 mil rect.-4 mil	2×10^{-3} ft. cd.	30 dB	1 μsec.	1 kHz	No
RSI	Polar Photodiode Array	1 mil	<1 $\mu W/cm^2$	60 dB	<1 μsec.	6.3 kHz	Yes
Bucket Brigade	Rectangular	3 mil	1 ft. cd.	18 dB	10 μsec.	60 Hz	No
CCD	Rectangular	2 μm	<10 ft. cd.	30 dB	1 μsec.	<1 kHz	No
CID	Rectangular	3 mil	0.1 ft. cd.	20 dB	<0.3 μsec.	30 Hz	Yes

IV. OPTICAL CORRELATION PROCESSORS

A. Discussion of Optical Correlation Techniques

The devices which hamper the development of real time optical computers at present are the electro-optical input devices. These are devices which transform the electrical signal representation of an image to a coherent optical image in real time. The state-of-the-art in these devices was the subject of the first phase of this program and the results of that investigation were reported in the Interim report [4-1]. A brief review of these devices, which include the General Electric Coherent Light Valve, the Hughes Liquid Crystal Modulator, and the ITEK Pockel's Readout Optical Modulator along with some recent development in other devices, is given in Section III of this report.

Two basic techniques for optical correlation which find wide application are described below. One of these involves joint transform correlation in which both input images are placed side by side in the input plane of an optical processor. The Fourier transforms of the two images are superimposed onto a storage device such as the PROM, which is assumed to have a linear region of the amplitude transmittance versus exposure curve, and the correlation components are then formed by a second Fourier transformation [4-2]. The retransformed image contains the autocorrelation terms on axis and two cross-correlation terms off axis by a distance of twice the input image separation. A digital simulation of this technique is presented in Section VI of the Interim Report.

The second method involves the holographic recording of a filter function produced by one of the input images. Lohmann gives eight different ways in which the hologram may be generated and discusses the advantages and disadvantages of the various methods [4-3]. Figure 1 shows the relation of the input image, the filter and the lens and Figure 2 presents a list of features of the various methods. In the figures u(x) is the complex amplitude transmittance of the unknown object, and v(x) the complex amplitude transmittance of the reference placed in the transform plane of the first of two successive transform lenses in the system. The complex amplitude term incorporated in a Fourier hologram in $\tilde{\mu}(x/2f)$ or $\tilde{u}^*(x/2f)$ is defined as

$$\tilde{u}(v) = \int u(x) \exp(-2\pi i v x) dx$$

where * denotes the congugate. For Fresnel holograms at a propagation distance z = f the corresponding terms are $\hat{u}(x)$ and $\hat{u}^*(x)$ where

$$\hat{u}(x) = \int \tilde{u}(v) \exp \{2\pi i[vx + (f\lambda)\sqrt{1 - \lambda^2 v^2}]\} dv$$

The prepare column having a negative sign indicates that the reference signal, v(x), cannot be used directly and must be made into a hologram before it can be used as the coherent filter. The next two columns for $\Delta\eta$ and Δx_s which contain minus signs indicate stringent coherence either spectrally or spatially. The columns δx_o, δx_R, and δx_D containing minus signs refer to the need for careful lateral adjustment in the object, reference, and detector planes. Adjustments in the reference plane may be on the order of a few microns. The arrows connecting two columns indicate dependent adjustments. The requirement for precise registration of the image transform and its filter does not apply to the joint transform correlation technique. The N_p column refers to the sensitivity to phase noise. The capability of measuring shifts between the object and the reference is indicated by a plus sign in the shift column.

Method No. 1, which is Vander Lugt's coherent matched filtering method has been used to measure the shift between two images of cloud formations.

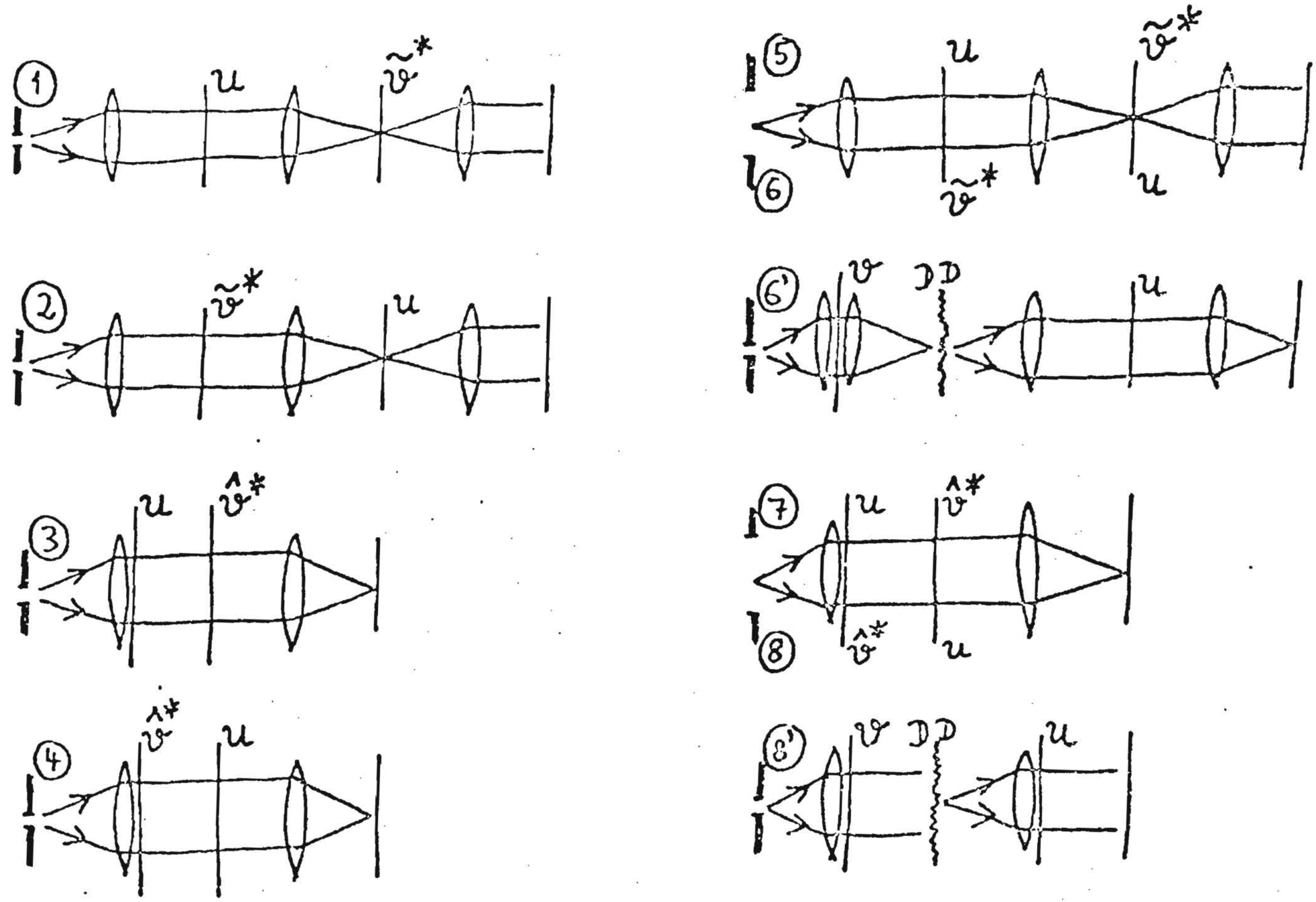

Figure 1. Different arrangements for holographic optical correlation. (From Ref. 4-3)

Nr.	input	reference	prepare	$\Delta\lambda$	Δx_s	δx_o	δx_R	δx_D	N_P	shift
1	u	$\tilde{v}^*$	−	−	−		−		−	+
2	$\tilde{v}^*$	u	−	−	−	−			−	−
3	u	$\hat{v}^*$	−	−	−			−	−	−
4	$\hat{v}^*$	u	−	−	−			−	−	−
5	$\|u\|^2$	$\tilde{v}^*$	−	−	+		+		+	+
6,6'	$\|\tilde{v}\|^2$	u	+	+	$(+)'$	+	+	−	−	−
7	$\|u\|^2$	$\hat{v}^*$	−	−	+				+	+
8,8'	$\|\hat{v}\|^2$	u	+	+	$(+)'$				−	+

Figure 2. List of Features of holographic correlation methods. (From Ref. 4-3)

Some of the methods make use of incoherent signals and thus simplify the input device to the optical system. The first four of the methods are old while the last four are new.

The joint transform technique has the advantage that the accurate alignment of the filter is reduced as compared to Vander Lugt filtering. The input objects can be placed anywhere along the optical axis in the input light beam as long as they remain in the beam and are coplanar. The two input images must be coplanar and the correlation results are largely sensitive to rotation and size of the two images.

None of the methods is ideal in all respects, but the method best suited for a particular application must be selected based on the demands of the application.

Some recent developments in the use of Mellin transforms have been claimed to reduce the dependence on image size and rotational orientation between the input images [4-4]. Shift or positional invariance in an input image is eliminated by forming the magnitude of the Fourier transform of the input image. This eliminates the effects of positional shifts in the input function since they appear as phase angles of the complex transform components. The effects of rotation and scale change on the transform components are separated by performing a rectangular to polar transformation on the Fourier transform components. A scale change in the transform coordinates does not effect the angular coordinate in the polar transformation while it scales directly the radial component. This reduces a two dimensional scaling of the input to a one dimensional scaling of the transformed function.

A single dimension Mellin transform on the radial component in the polar transformed data should produce a scale invariant transform due to the scale invariant properties of the Mellin transform. The rotational variations of the input are converted to phase factors by performing a single dimension Fourier transform in the angular dimension of the polar transformed information.

A digital simulation of this technique of eliminating size and rotational variations of the input images was attempted late in the contract period. Time did not allow for the simulation to be developed to a point of producing conclusive results.

Figures 3 and 4 are examples of how a joint transform correlator and a Vander Lugt correlator could be constructed. These two examples do not meet the requirements of a real time optical correlator since they use as input media transparencies which are not real time input devices capable of operation at television frame rates.

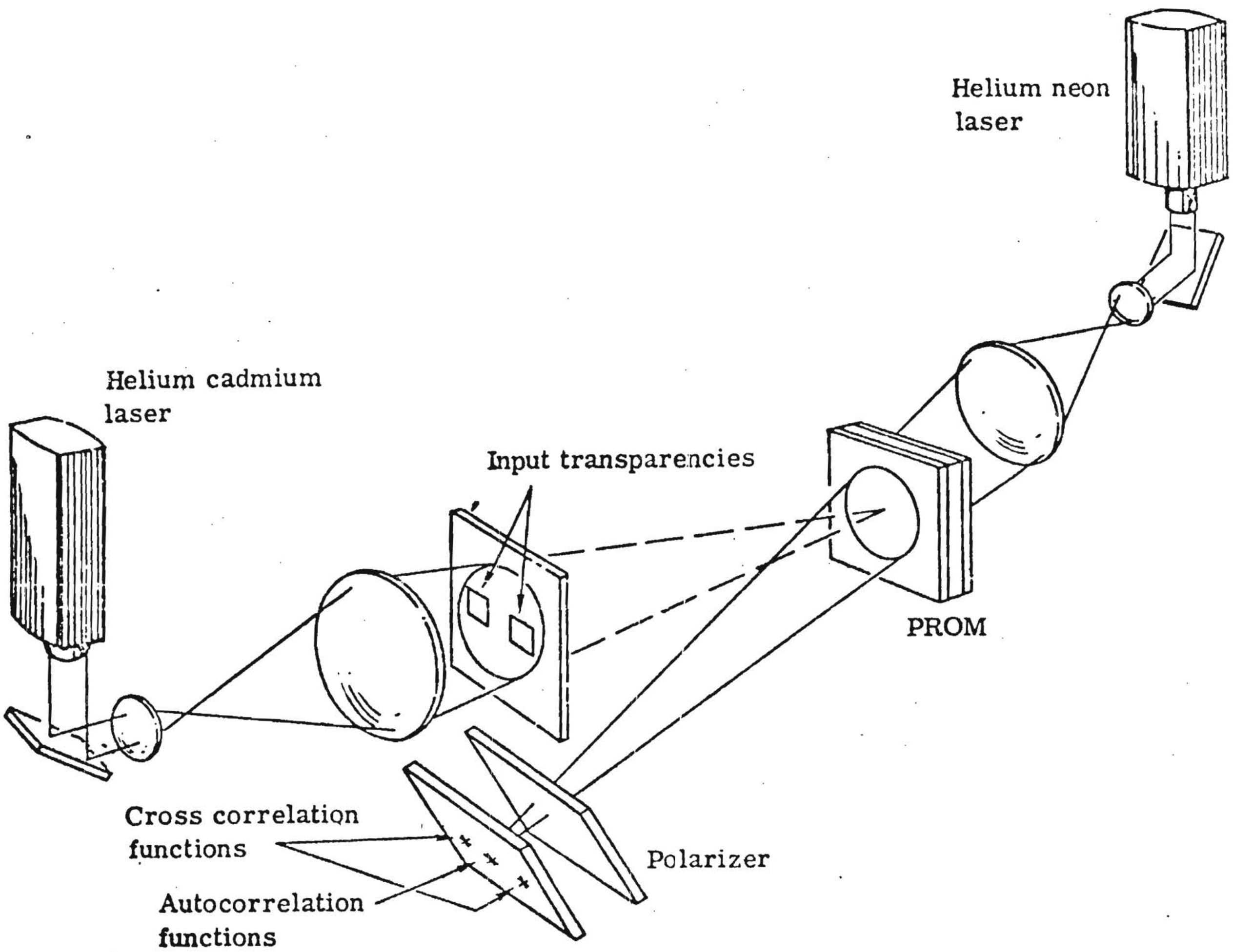

Figure 3. Joint transform correlator using PROM.
(From Ref. 4-2)

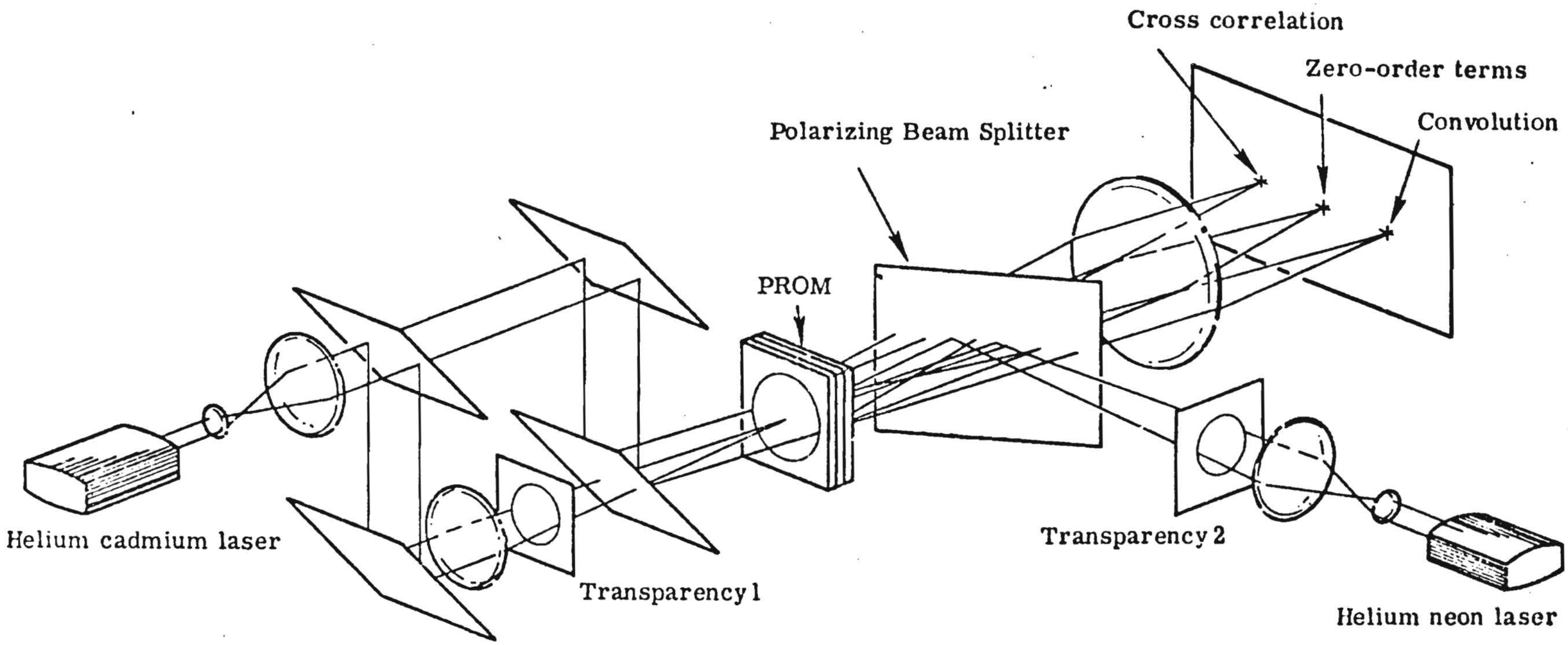

Figure 4. Vander Lugt correlator using PROM.
(From Ref. 4-2)

V. SOME CONSIDERATIONS OF DIGITAL IMAGE PROCESSORS

Many of the personnel with whom discussions regarding optical processing have taken place during the project period have indicated a belief that in a few years, possibly five, digital processors will replace optical processors. This supposition applies to such areas as synthetic aperature radar processing where optical techniques have been developed to a high degree of perfection. This feeling is due, at least in part, to the very rapid advancement in digital systems and in the techniques of using these systems. The following is a brief review of some of the present considerations in digital image processing so that the trade-offs between digital and optical processing can be better appreciated.

The time required to perform a one dimensional fast Fourier transform, (FFT), using the Cooley-Tukey method and using a general purpose computer performing calculations serially is [5-1]

$$T_c = 2kN \log_2 N \text{ (seconds)}$$

where N = number of points in transform,

k = constant depending on particular computer and program.

The indicated reference gives $k = 30 \times 10^{-6}$ seconds for an IBM 7094 computer.

To perform a two dimensional FFT requires that the single dimension transform be taken in one of the dimensions of the input data, say along the rows of an image - which corresponds to the normal method of generation of a TV picture - and that the transform then be taken along all the columns of the row transformed data.

If the number of rows is represented by N and the number of columns by M, the time required to transform the entire picture using the Cooley-Tukey algorithm is

$$
\begin{aligned}
T_{2c} &= (2kM \log_2 M)N + (2kN \log_2 N)\ M \\
&= 2\ k\ MN\ (\log_2 M + \log_2 N) \\
&= 2\ k\ MN \log_2 MN \text{ (seconds)}
\end{aligned}
$$

If the picture is square $N = M$

$$
\begin{aligned}
T_{2c} &= 2\ k\ N^2 \log_2 N + 2\ kN^2 \log_2 N \\
&= 4\ kN^2 \log_2 N \text{ (seconds)}
\end{aligned}
$$

Applying a filtering operating in the transform or spatial frequency plane requires that the transform be multiplied by the transfer function involving N^2 operations, and the time $T_f = k_1N^2$, where k_1 is the time required to read the memory, perform the multiplication, and write into memory. Retransforming the filtered spatial frequency plane to obtain the filtered input function would again require a number of operations equal to

$$T_{2c} = 4\ kN^2 \log_2 N$$

The total time involved in the digital computation of the filtered function, with the exception of the k's representing the computation time, agrees with that given by Hall [5-2]

$$
\begin{aligned}
T_{2cf} &= 4k\ N^2 \log_2 N + k_1\ N^2 + 4\ k\ N^2 \log_2 N \\
&= 8\ k\ N^2 \log_2 N + k_1\ N^2 \\
&= N^2\ (8k \log_2 N + k_1)
\end{aligned}
$$

The time required to compute a single dimension transform by the direct method is

$$T_d = kN^2$$

The time required to perform a two dimensional transform of an N x N matrix by the direct method transform is

$$
\begin{aligned}
T_{2d} &= kN^2(2N) \\
&= 2kN^3
\end{aligned}
$$

The time required to perform two dimensional filtering (transform, filter and retransform) by direct "brute force" methods would be

$$T_{2df} = 2kN^3 + k_1N^2 + 2kN^3$$
$$= N^2(4kN + k_1)$$

Using the constant k given for the IBM 7094 computer some representative times may be calculated for the computation of the two dimensional transform of several sized N x N images.

CALCULATION TIMES

Single Dimension Transforms			No. of Single Dimension Transforms	Two Dimensional Transforms	
N	T_d(sec)	T_c(sec)		T_{2d}(sec)	T_{2c}(sec)
32	0.031	0.010	64	1.97	0.61
64	0.123	0.023	128	15.7	2.95
128	0.492	0.054	256	126	13.8
256	1.97	0.123	512	1009	62.9
512	7.86	0.276	1024	8053	283
1024	31.5	0.614	2048	64425	1258
2048	126	1.35	4096	515396	5536
4096	503	2.95	8192	4123169	24150
8192	2013	6.39	16384	3.30×10^7	1.05×10^5
16384	8053	13.8	32768	2.64×10^8	4.51×10^5

Our experience on the Univac 1108 computer with a single dimension FFT of length 256 was that the computation time was approximately 0.12 sec and for a 1024 point transform was 0.6 sec [5-3]; these times agree well with the above calculations based on the IBM 7094 computer calculation times.

The General Radio (GenRad) time series analyzer can perform a single dimension 1024 FFT in 12.2 msec. It is a special purpose analyzer vintage early 1970's [5-4].

For the filtering operation for large dimension images the computation times would be approximately double those indicated above for the two dimensional transforms since the transform would have to be taken twice and the time for the spatial filtering operation for large dimension arrays would be small compared to the transform times involved.

The above estimated times assume that the computer memory is large enough to contain the entire image data set. The image data set is an N x N array of brightness level each requiring two computer words since the transform process produces complex transform components. An N of 128 which produces a 128 x 128 array was the largest that could be used in the 65K main memory of the U-1108. This represents $2^7 \times 2^7 \times 2 = 32K$ words of memory for the image data and storage must also be allocated in the main memory for the program used for the calculations.

In most practical situations and for large images all the image data could not be present in the main memory at the same time. Future semi-conductor memory developments will probably make possible such large memories. Presently, for large images, the data must be brought into the main memory piecemeal. This is efficient for the first transform operation for a two dimensional transform since the data is generated serially (in rows). A problem is then encountered when the input data matrix must be transposed so that the second transform operation can be performed (along the columns of the transformed data). This in the past has consumed more computer time than actual transform operations. Billingsley [5-5] states that the expenditure of computer time for a two dimensional transform is primarily for the 90° rotation for the x, y separate transform processes and that the transform process is "neatest" if the data arrays contain a number of samples which is a power of two, which restricts the image size increments.

Techniques have been developed which reduce the matrix transposition time (for a 1024 x 1024 matrix) from several tens of minutes to several minutes by performing the matrix transposition on subelements of the data array and storing the results of these operations in extended memory. These subelements are of dimensions which are power of two factors of the larger array [5-6]. The times indicated are for a CDC 6600/7600 computer and make use of a sizable extended core memory.

Another technique which requires no extended memory is presented by Eklundh [5-7]. This technique reads in the row oriented data and performs the row transforms. The number of rows read in depends on the size of the central memory available. As few as two rows can be processed in main memory to obtain the transpose matrix at the expense of having to read the data set more than one extra time. The more rows which can reside in main memory at one time the shorter the computation time of the transpose matrix. Eklundh states the time required to transpose a 1024 x 1024 matrix of data points for 32 rows in main memory at one time is:

Central Processor Time =	23 sec
Estimated Input-Output Time =	134 sec
Total Time	157 sec

Special purpose pipeline and parallel FFT processors can speed up the time required for calculation of the transforms considerably but restrict the flexibility of the digital processors.

Several techniques are used to speed up the calculation of the FFT. One splits the single dimension transform into a two dimension transform of a size which is an integer factor of the transform size N. The transform is then computed on the smaller radix set of data points. For example a 64 point transform can be split into four rows of 16 points each, the transform of the rows taken, the columns then arranged as four 4 x 4 matrices and the transform of each row again obtained [5-8]. The "elementary computation" element in a "decemation in time" algorithm for a radix 2 transform involves the calculation of

$$A' = A + CW^i$$
$$C' = A - CW^i$$

where A and C are complex input data points and $W = \exp(j2\pi/N)$, and i is an index which is a function of how many steps have been completed in the algorithm. A radix 2 algorithm would require eight memory cycles, four multiply cycles, and six add cycles for each of the $(N/2)\log_2 N$ elementary calculations. The number of elementary calculations required in the FFT computation is given by

$$C_r = \frac{N}{r} \log_r N$$

where N is the number of points in the transform and r is the radix. If r=n, $C_r = 1$, but the complexity of the elementary calculations increases with r. Thus this technique appears to increase the FFT computation speed by possibly a factor or two or four before the complexity of the hardware becomes prohibitive.

Some examples of the speed of higher radix designs are given by Corinthios [5-9]. He gives the computation time and maximum sampling rate of the input data for the calculation of a 4096 point transform as a function of radix as:

Radix	Computation Time (Msec)	Maximum Sampling Rate (Samples/Sec)
2	9.5	430,000
4	3.6	1,080,000
8	1.85	2,100,000

Later developments led to a further increase in the processing speed of r + 1 where r is the radix [5-10]. Here assuming that the operations can be performed at the data shifting clock period of 100 nsec a 1024 point radix 4 transforms can be obtained in 64 msec which amounts to a maximum sampling frequency of 16 MHz. This time is obtained from Corinthios' expression for the time for transforming N real valued data in real time as

$$t = \frac{1}{2}(n)\left(\frac{N}{r}\right) t_{sh}$$

where $N = r^n$ with r the radix of the transform, and t_{sh} is the minimum data shifting period. A two pass fast Fourier transform processor for image processing applications is described by Buijs, et al. [5-11]. The processing rate is one clock cycle per input point for the N-point transform regardless of the value of N chosen. The implementation uses two radix $N^{\frac{1}{2}}$ passes carried out in parallel and in which each $N^{\frac{1}{2}}$ point transform is carried out via a serial input parallel output transform circuit. The processing rate is expected to be nearly 5 MHz. This technique appears to be relatively advantageous for small N (a 64 x 64 transform being implemented). For a clock rate of 200 nsec the processing rate should be approximately 200 msec for a 1024 point transform.

A new hardware realization of higher speed Fourier transforms described by Liu and Peled [5-12] should make possible a throughput of complex data points at a 25 MHz rate using standard available TTL integrated circuits. Their approach should offer an "attractive alternative" up to transform lengths of 1024 points.

VI. CONCLUSIONS AND RECOMMENDATIONS

Part one of this investigation was carried out to determine the feasibility of an optical processor for on-board spacecraft operation. The investigation revealed that although real time optical processing is much nearer a reality than it was several years ago, there are still components critical to real time operation which need further developing and refinement. Among these critical components are the incoherent-to-coherent optical input devices for the object and filter planes, and the high resolution detector arrays for the output plane. Much of part one of this effort was directed toward an investigation of the impact of the operating characterisitics of these devices on system performance, since these are, at present, the critical components of a real time optical processor.

The final success of a real time optical processor will depend in large part on the performance of the image input devices, which will be employed in both the input plane and the frequency domain filter plane. Photographic transparencies have traditionally been used for these functions; however, because of processing time delays, photographic film can hardly be classed as a real time input medium. While devices to provide the function of image inputting and filter function insertion in the transform plane display some similar characteristics, the demands on each of these devices are different. It would be desirable for the input plane device to be capable of inputting high contrast images at television rates, with erasure or write-over capabilities such that an image written on the input device at a television rate would be independent of previously written images. The input plane device should also be able to accomodate high resolution television images or images generated from multispectral scanners. The filter plane devices should also be capable of inputting high contrast, high resolution images to the filter plane of a Fourier optical processor, and in addition be capable of storing the image over an appreciable time interval. The filter function storage interval would be dependent on the application for which the processor is intended.

Four devices were considered in this investigation for the role of image input device. These were: (1) the General Electric Coherent Light Valve, (2) the electron-beam-addressed KD*P Light Modulator, (3) the ITEK Pockel's Readout Optical Modulator, (4) and the Hughes Liquid Crystal Modulator. Of these four devices the PROM and the Liquid Crystal Modulator appear at this time to be the best candidates for the real time optical processing applications because of their inherent operational simplicity, compactness, extended life-time, and future development prospects. However, neither of these devices is completely satisfactory in its performance of the desired functions for an image input device and additional development work is required. Techniques for optimum systems applications of these devices should also be investigated.

Output plane detection devices provide another optical processor interface where device characteristics are important. The information in the output plane of an optical processor is in the form of a spatial distribution of light intensity. The detector should sample at discrete points or scan the output plane with sufficient resolution to extract the details of the processing operation. A review of solid state detection devices was carried out. The exact specification of an output plane device is dependent on the processor application, and should be selected on the basis of operational compatibility.

The mechanical design of an on-board optical processor is important to successful operation in a spacecraft mission. The general mechanical design considerations for an on-board optical processor were discussed. Guidelines have been suggested for establishing the mechanical specifications for an on-board optical processor designated for a specific mission.

The electronic interface with the optical processor is also not specifically defined at this time. Since it appears highly probable that the input to the optical processor will be an electrical signal in the form of a time waveform, and not a direct optical input, some unique electro-optical interface problems arise with the potential image input devices. The excitation for the input devices is generally an incoherent light image which must be generated from the time waveform representing the input signal to the processor. A discussion was presented of potential electrical-to-optical interface devices such as cathode ray tubes, storage tubes, and modulated laser beams. Imaging of these electrical-to-optical interface devices in the input plane of the incoherent-to-coherent input devices is also discussed. Recommendations concerning the interface electronics at this time are, that since there are so many unknowns in both the electrical-to-optical and optical input devices, a laboratory breadboard should be constructed to provide a test bed for the evaluation of real time input techniques.

A preliminary digital simulation of several potential problems relating to real time operation of an optical processor was presented. Specifically considered were the optical correlation of two input images by the spatial heterodyning technique, and the effects of image decay on the correlation plane light intensity distribution. The results of this preliminary investigation strongly suggest that additional simulation studies be performed to evaluate the correlation signal degradation for complex coherent images which are subject to image decay resulting from the short relaxation times characteristic of some coherent input devices. These advanced studies would also serve to define the required parameters for the correlation plane detector.

From the results of part one of this study it is recommended that a program leading to the development of an on-board coherent optical processing system be mission-oriented, and include the following elements: (1) select a specific spacecraft mission for which an on-board optical processor would significantly improve data management operations, and provide additional benefits in the reduction of system cost and complexity, (2) continue digital simulation of optical processing operations to define system requirements, (3) initiate the development of or modification to a real time optical input device which would be compatible with the spacecraft sensors for the selected mission, and (4) assemble a breadboard optical processor to allow experimental evaluation of the complex electrical-to-optical and optical-to-electrical interfaces.

Part two of the investigation was concerned with the applications of optical data processors, specifically those systems relating to satellite data acquisition. Discussions with personnel knowledgable with future space missions have revealed that on-board data processing of any kind which would eliminate some of the available data is not acceptable at this time. Returning all the available data to the earth and letting each investigator perform whatever data processing techniques he desires is the method of operation for space missions of the immediate future. This method of operation creates severe data storage problems. It is possible, however, that the severe technological problems associated with transmission, processing and storage of projected data acquisition systems will have a moderating influence on the currently held views which oppose preprocessing.

In addition, if on-board processing were to be considered, the general opinion at present is that it would be digital rather than optical. The reasons cited for this are (1) greater accuracy offered by digital processors, (2) greater flexibility of digital processors, (3) future developments appear better for digital as opposed to optical processors and (4) greater dynamic range of digital processors. A major disadvantage of digital processing is the time required to process a two dimensional image, and the high acquisition cost of these systems. It should be pointed out, however, that the preference for digital processing is due in part to its relatively mature hardware technology, and the general feeling that optical processing is still a laboratory technique.

Systems employing optical data processing may well find applications for on-board processing when spacecraft are designed for operational rather than research purposes. For such an application the exact nature of the data of interest would be known, and the redundant parts of the data could be eliminated without significant loss of information. Optical data processors may also find applications for purposes of "quick look" capabilities not requiring all the precision available from various sensors.

From the results of part two of the investigation it was determined that: (1) on-board data processing for the space craft missions now being designed is generally not considered desirable, (2) if on-board processing were to be considered it would probably be digital rather than optical at this time, (3) the exact configuration of an optical correlator would be determined by the specific application to be satisfied and (4) there have been significant advances in device technology relating to real time data processing system implementation.

Although the current concensus is that preprocessing or high speed optical spatial processing is not desirable for spacecraft data acquisition systems, pressures resulting from technological difficulties with advanced mission concepts may force a change in this opinion in the near future. It is our view that NASA should continue to look at optical processing technology as a potential component of a new generation of data acquisition and processing systems. When properly utilized, both optical and digital technology could be combined to form a hybrid system with increased flexibility and processing speed for applications in earth resources and space systems technology.

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